Documenting natural hazards in steep, densely forested regions with airborne laser swath mapping, western Cascade Range, Washington

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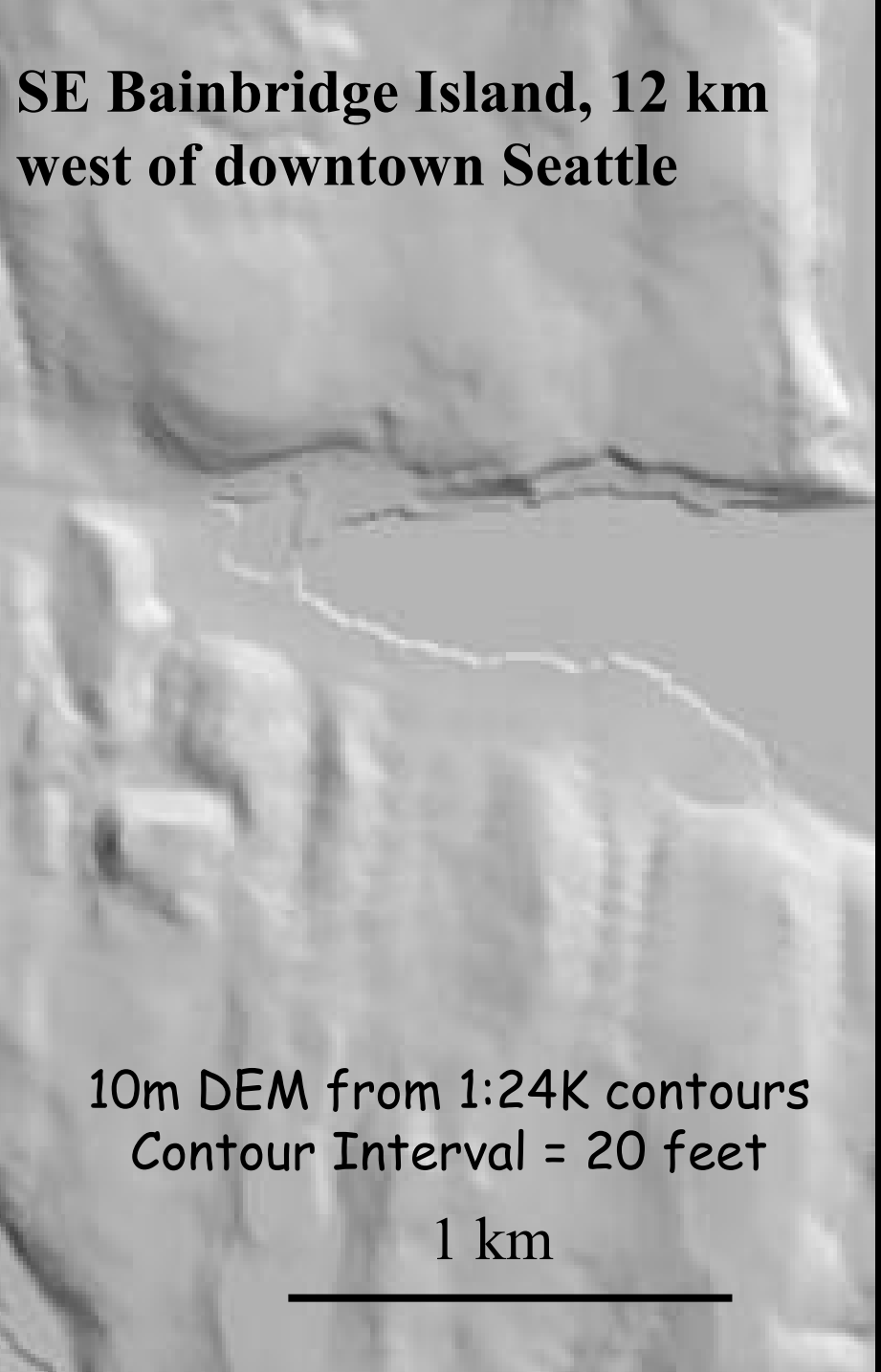
NASA-SENH program review, 3-5 May 2005

Project goals:

- Improve natural hazards science
- Help commercialize ALSM (lidar) technology

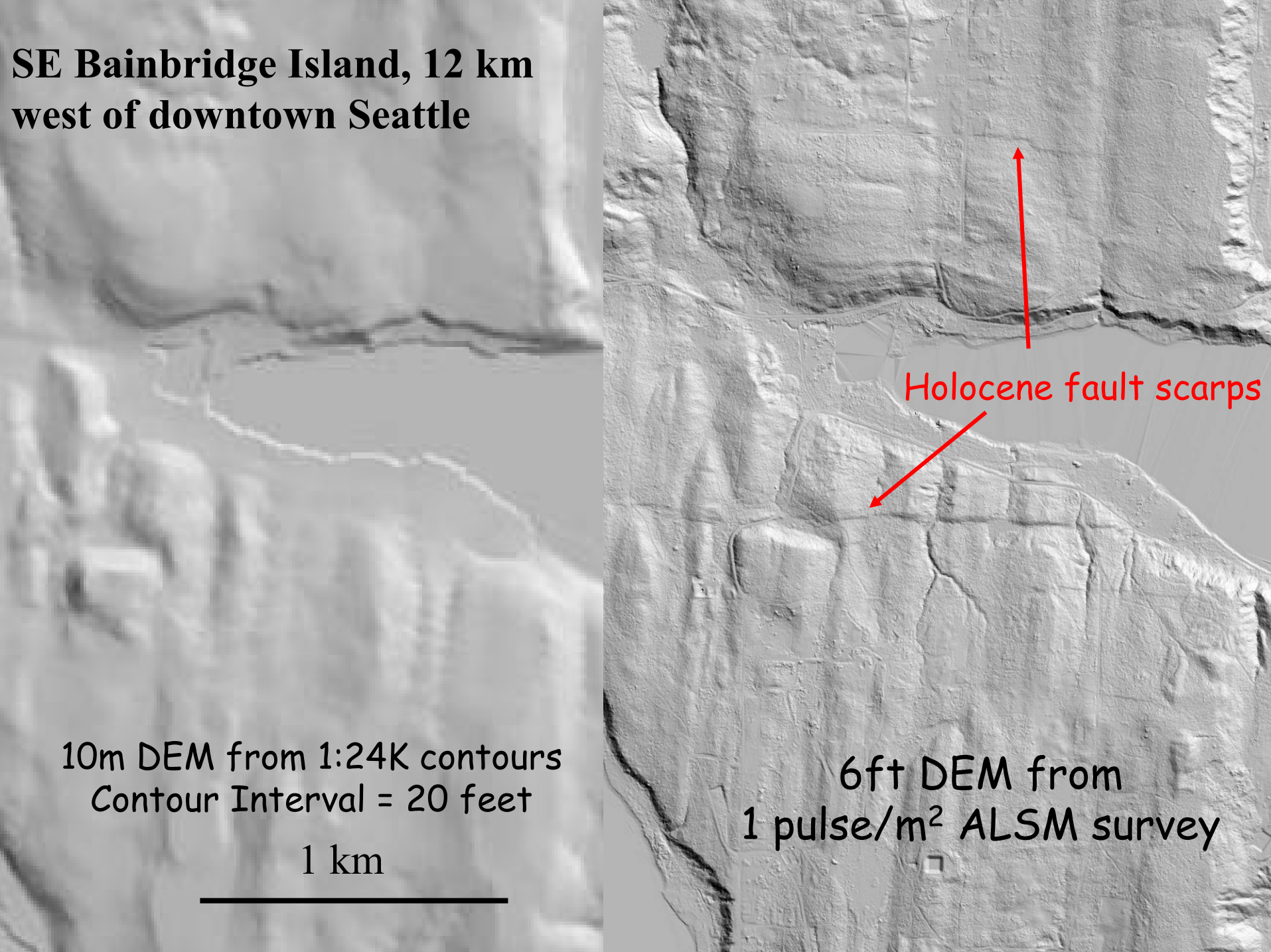
Outline

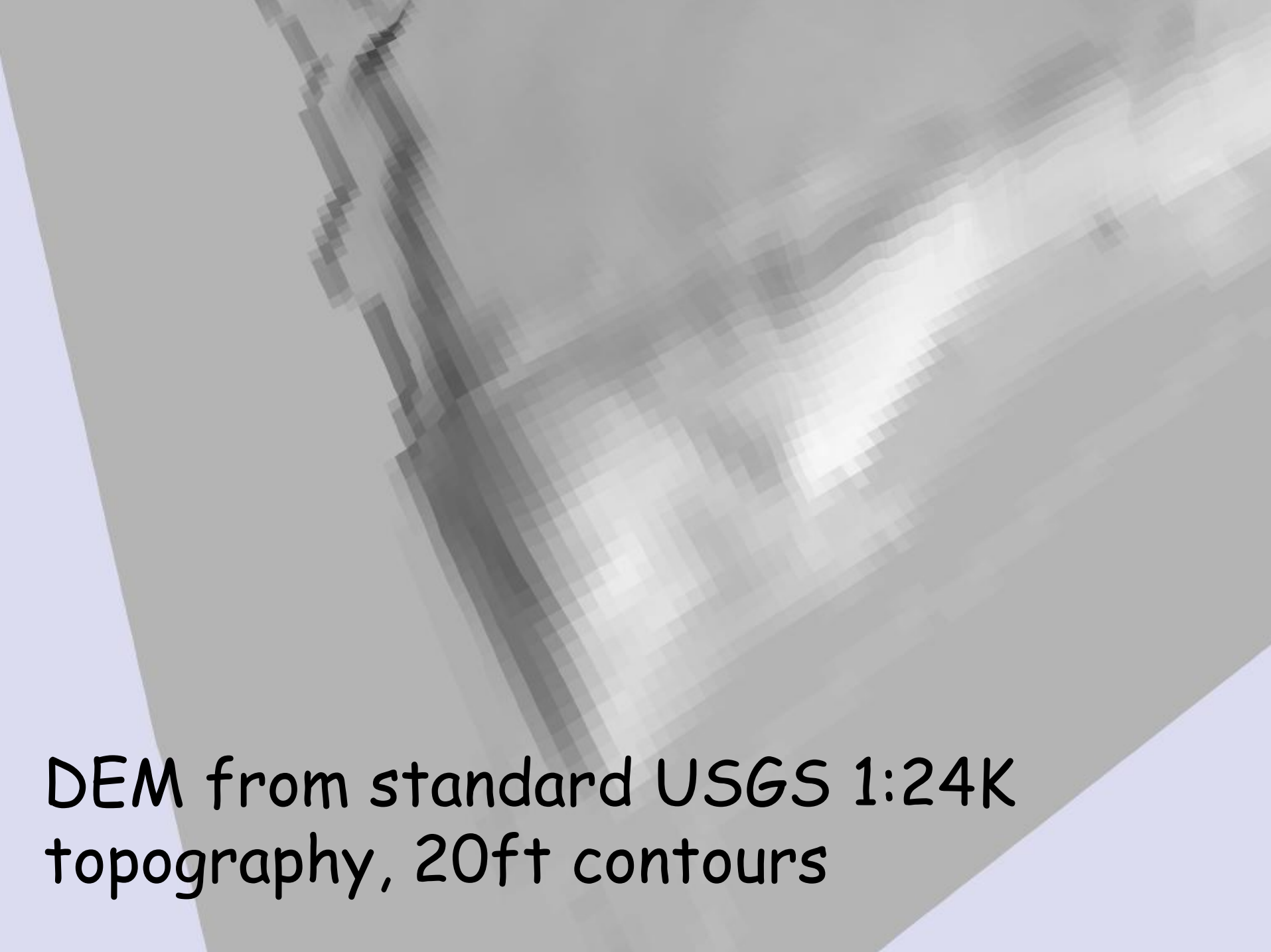
- Introduction
  - Why better topographic data?
  - ALSM / Lidar technology
  - History of this project
- Contract specifications and quality assurance
- Using high-resolution topography for hazards studies
  - Fault inventory
  - Geomorphic mapping
  - Topographic change at Mount St Helens



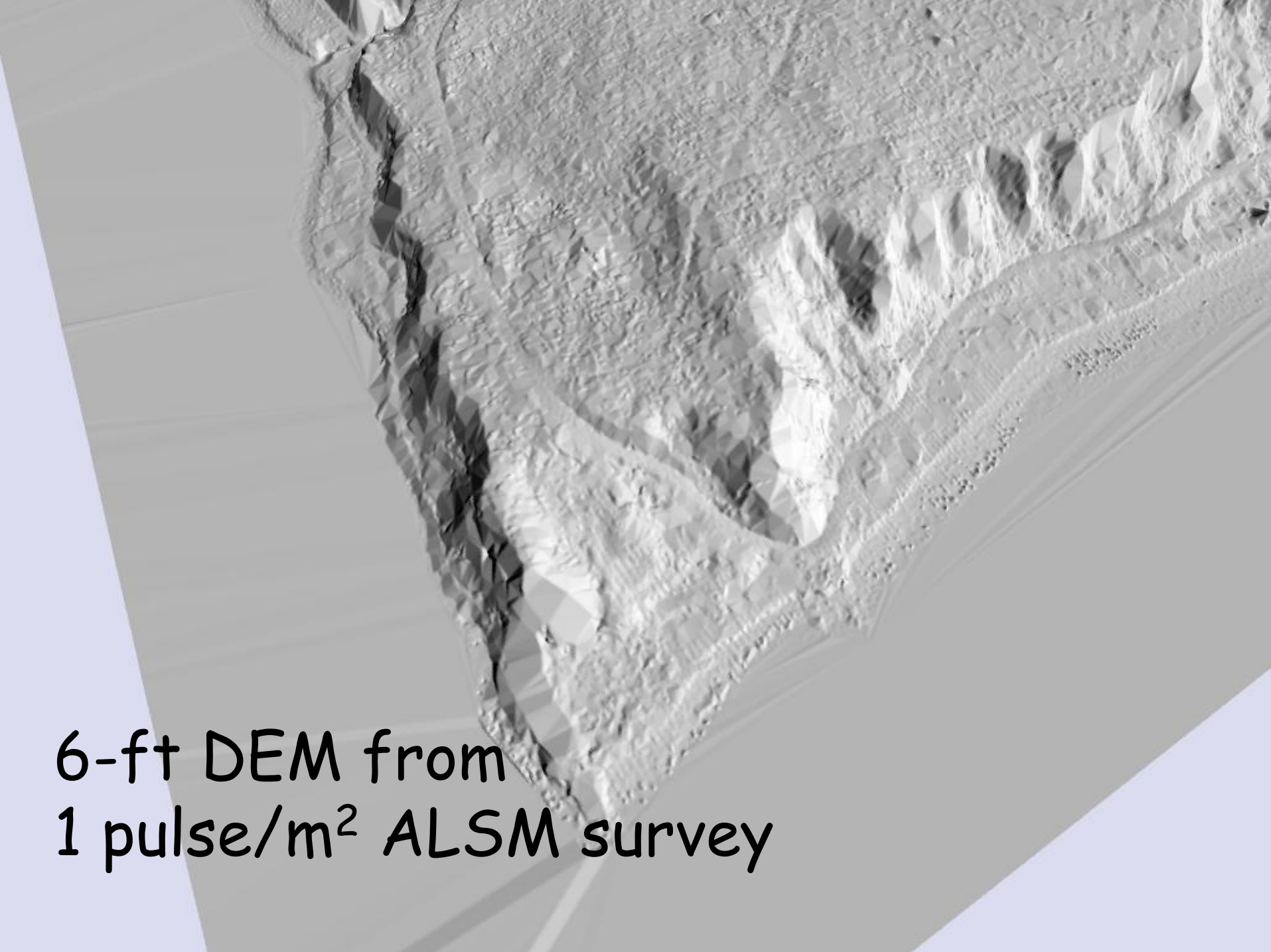
Why do we need better topographic data?

Continued

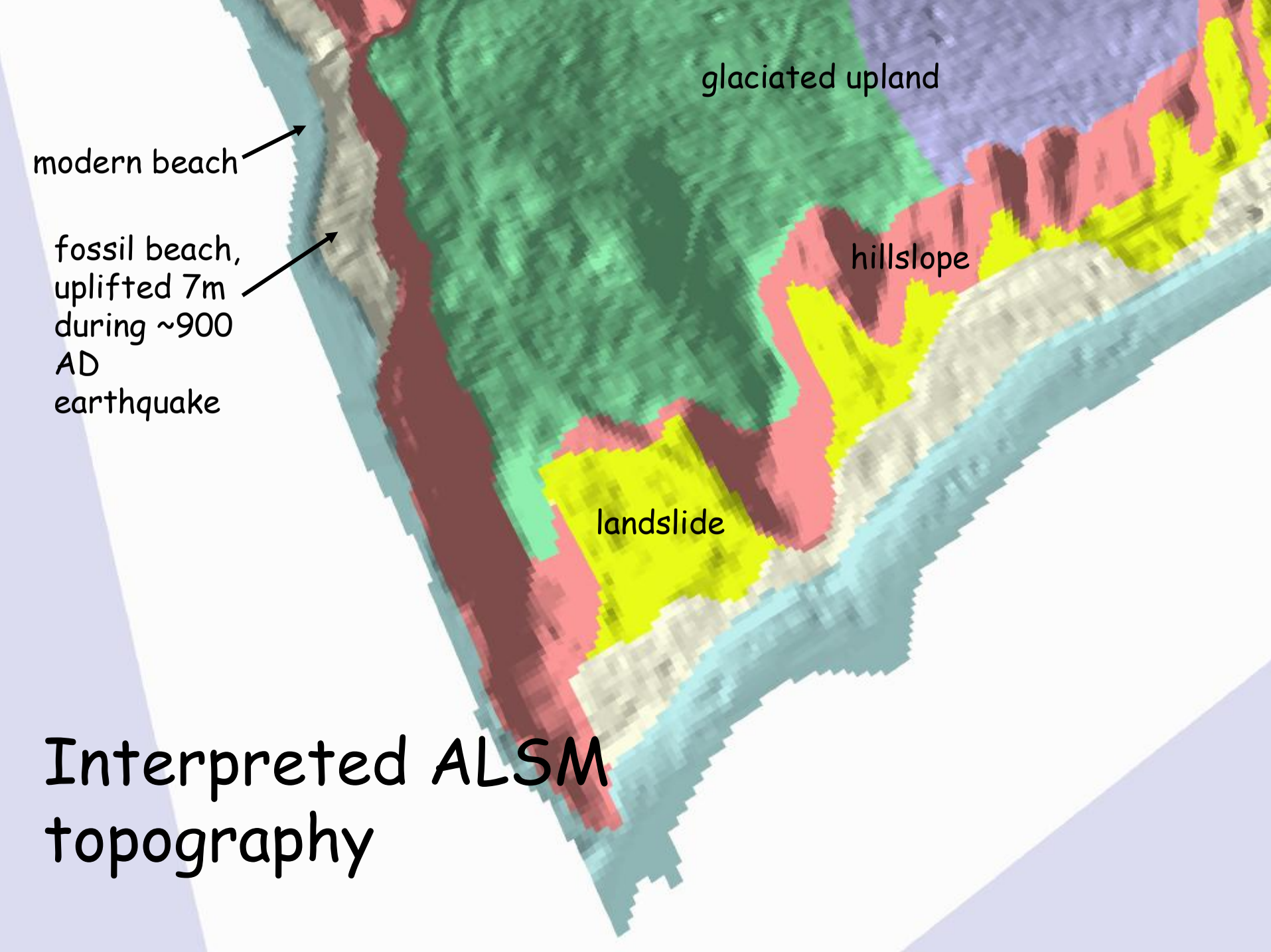

SE Bainbridge Island, 12 km west of downtown Seattle
Holocene fault scarps
10m DEM from 1:24K contours
Contour Interval = 20 feet
1 km
6ft DEM from
1 pulse/m² ALSM survey



DEM from standard USGS 1:24K topography, 20ft contours

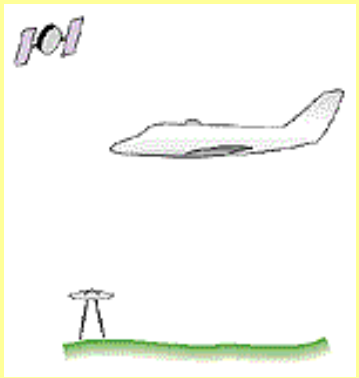


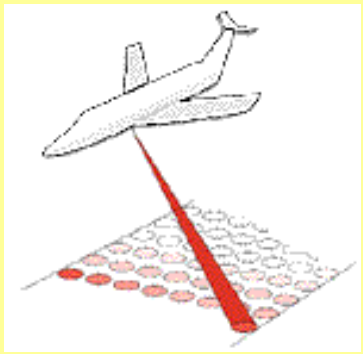
6-ft DEM from
1 pulse/m^2 ALSM survey



Interpreted ALSM topography

Lidar technology





graphic courtesy Natural Resources Canada
click either graphic to view movie

ALSM

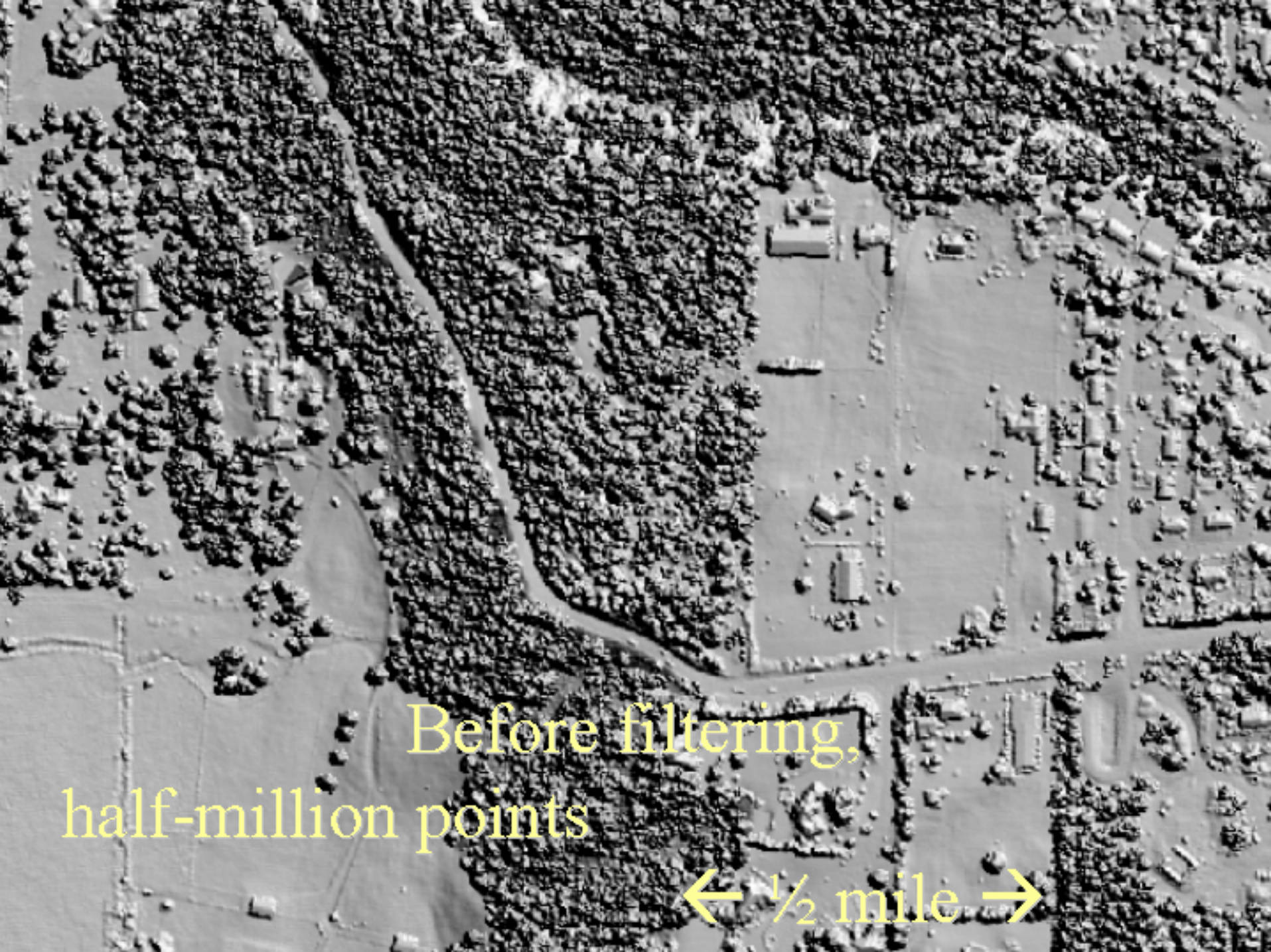
(**A**irborne **L**aser **S**wath **M**apping)

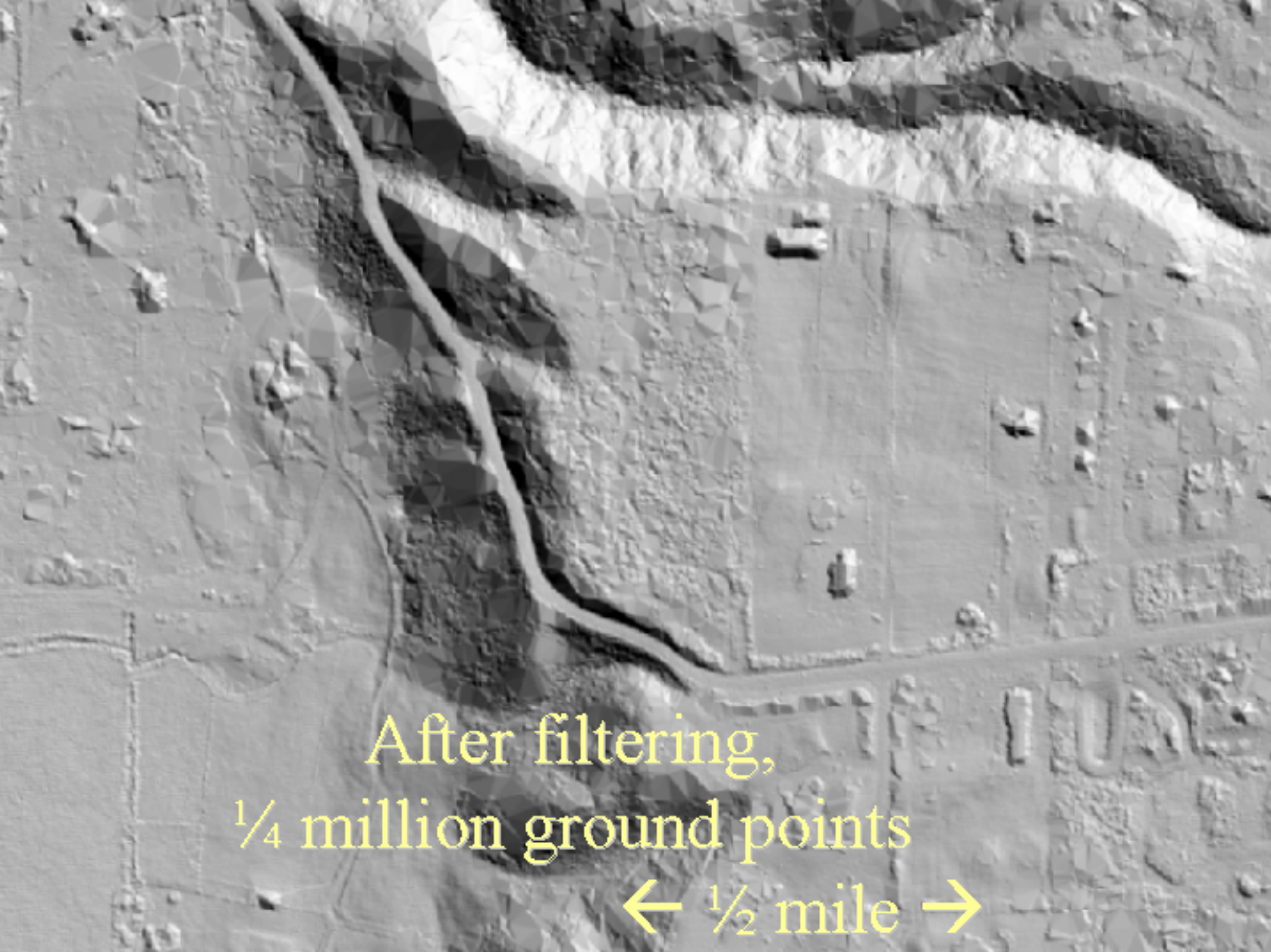
or

LIDAR

(**LI**ght **D**etection **A**nd **R**anging)

- Differential GPS—aircraft position
- Inertial measurement unit (IMU)—aircraft orientation
- Scanning laser rangefinder—scan angle, distance. May detect multiple returns from single laser pulse
- 3 data streams
  - GPS @ 1-2 Hz
  - IMU @ 1-200 Hz
  - rangefinder @ 20-100 kHz
- Extensive processing to get ground coordinates
- Post-processing to classify measured points as ground, vegetation, structure, …


Before filtering,
half-million points
← ½ mile →


After filtering,
¼ million ground points
← ½ mile →

History of this project

1996-7 Kitsap PUD lidar survey of Bainbridge Island

Greg Berghoff recognizes scarp along Seattle fault

1998-9 USGS digs 5 trenches across Bainbridge scarp

1999 3-yr, $300K NASA grant to acquire lidar data in search of Holocene fault scarps

Local government, USGS, & NASA staff form Puget Sound Lidar Consortium (PSLC)

City of Seattle commits $200K

Congress adds $500K to USGS budget for Kitsap County survey

PSLC requests proposals for lidar surveys

2000 PSLC awards survey contract to TerraPoint

2001-2 Congress adds $1M to USGS budget for Mason and Thurston county surveys

History of this project

By 2002, it was evident that (1) lidar works to find subtle fault scarps in low-relief areas, and (2) 'local' funding could be obtained to survey populated areas

We proposed to (a) test utility of commercial lidar in wetter, high-relief areas, and (b) fund acquisition of lidar data in less-populated areas that are seismically interesting.

Our plan was to survey three areas in Cascade foothills (2-3 meters annual rainfall, 1-2 km local relief), each with

- significant recorded seismicity
- volcanic-hazards interest
- landslide potential

History of this project

2002 3-yr NASA grant to extend lidar surveys to Cascade foothills (FY03-FY05): **West Mt Rainier**, **Darrington**, and **Mount St Helens** seismic zones

NASA awards contract for **West Mt Rainier** and northern San Andreas surveys to TerraPoint

West Mt Rainier surveyed—incomplete because of snowfall

2003 NASA awards contract for **Darrington** and **Mt St Helens** surveys to TerraPoint

West Mt Rainier survey completed

Darrington zone surveyed—incomplete because of snowfall

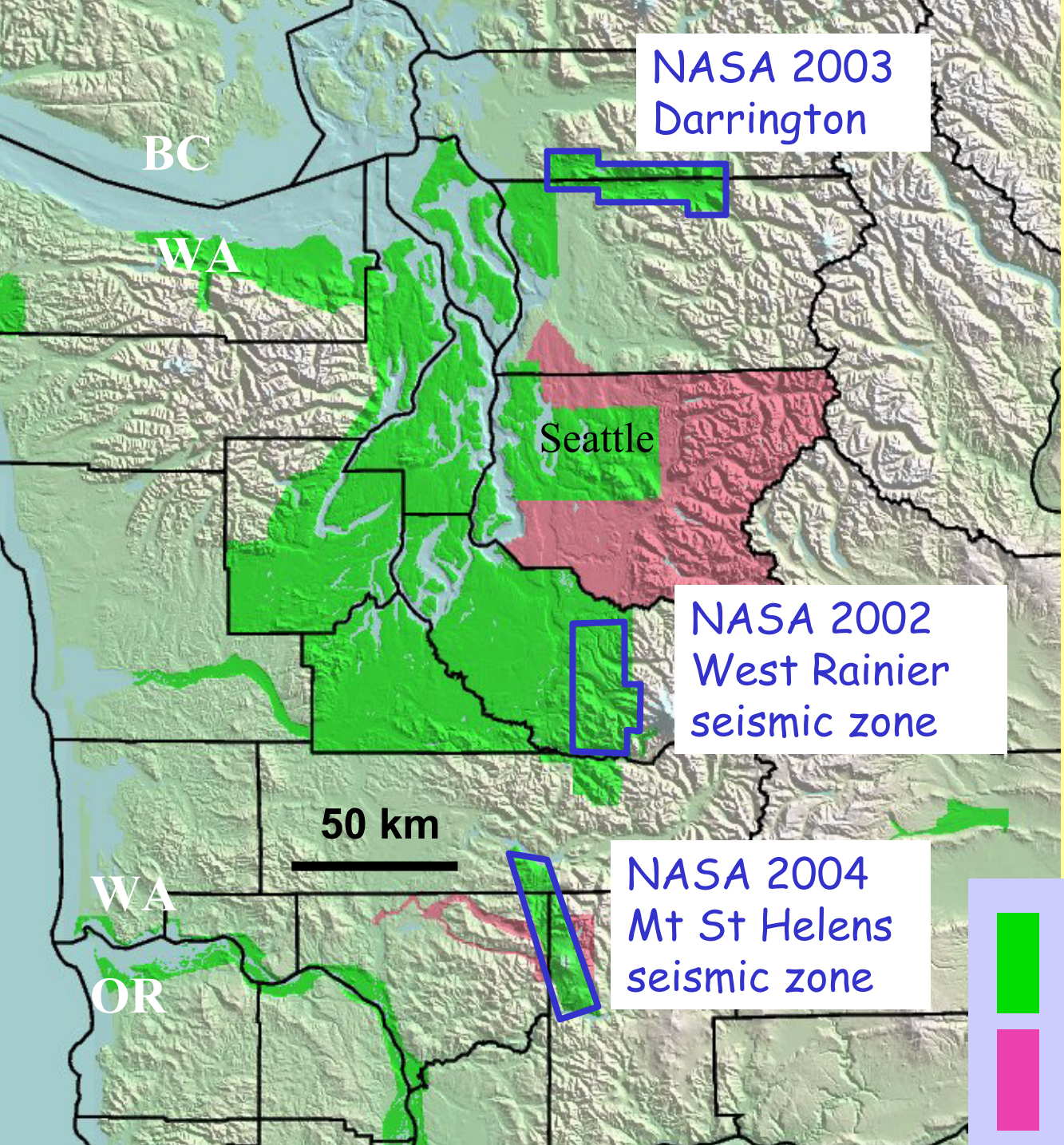
Congress adds $500K to USGS budget for Pierce County survey

2004 USGS Geography Discipline joins Puget Sound Lidar Consortium with funding for Lower Columbia survey

Mount St Helens wakes up. St Helens survey re-planned to capture changes associated with possible eruption

Darrington survey completed

Mt St Helens survey acquired

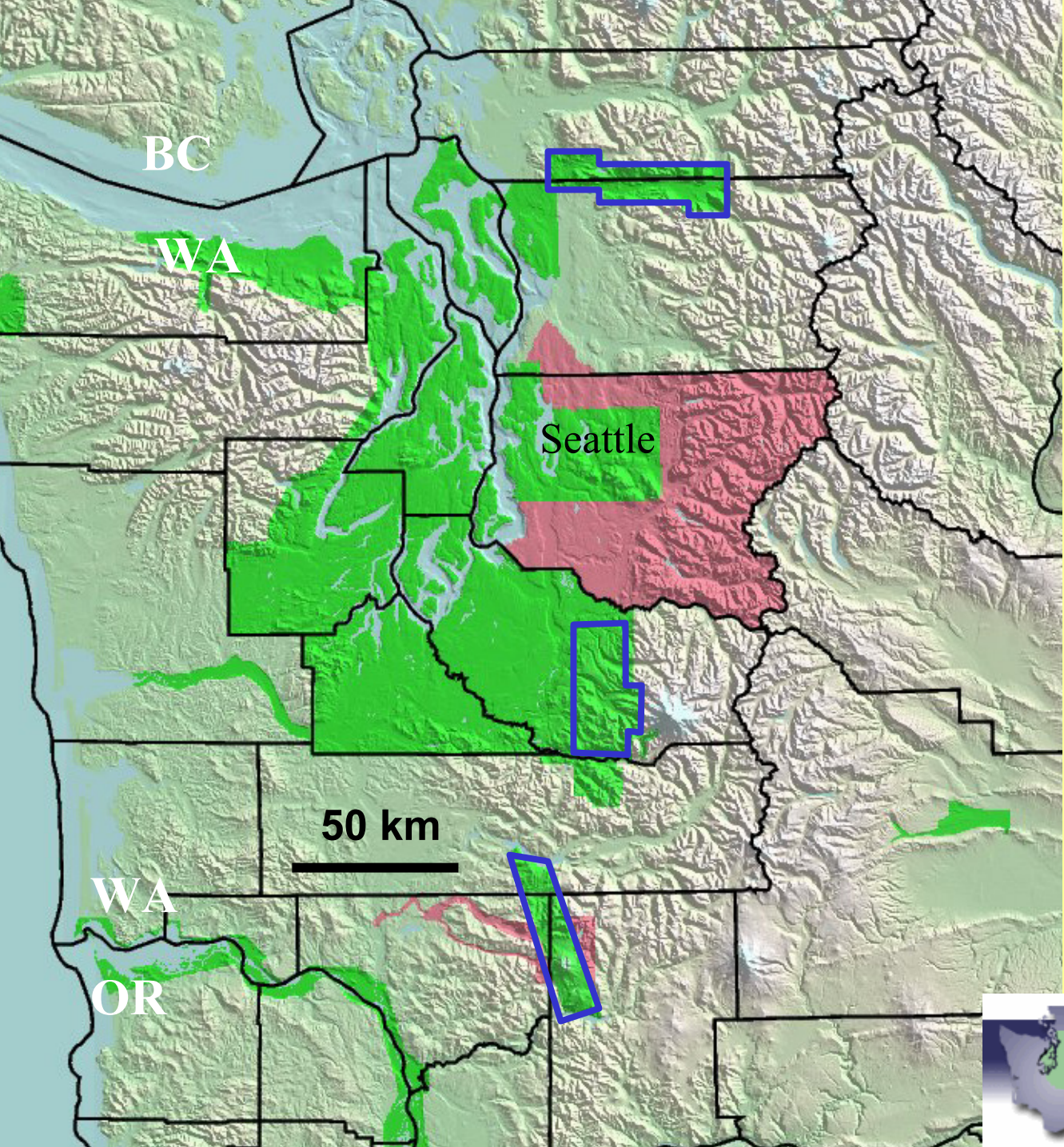


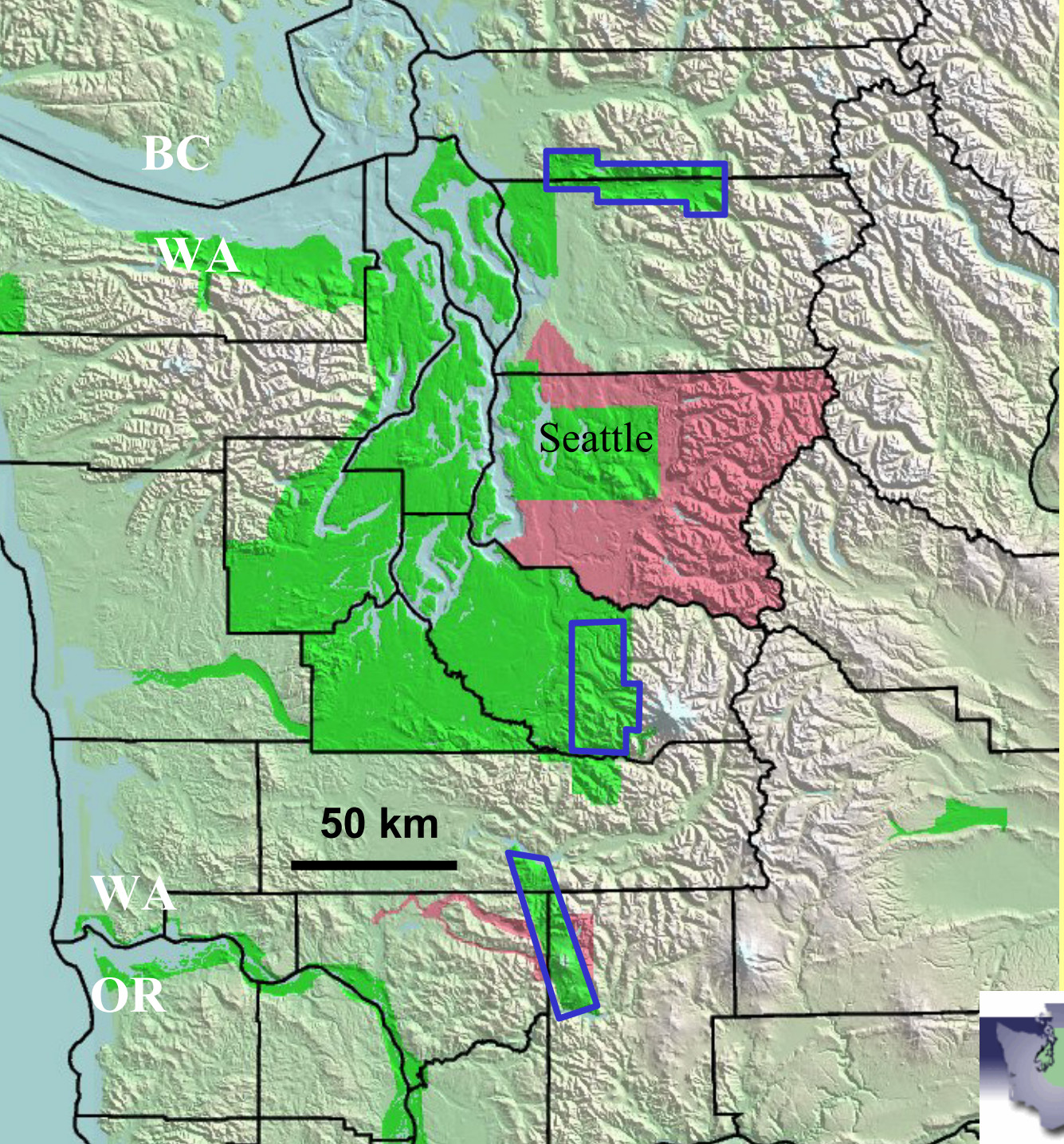
FY1999 - FY2005
Puget Sound
Lidar Consortium
and NASA:

>15,000 km^2 of
high-resolution
public lidar
topography

Puget Sound Lidar Consortium and NASA

Other public surveys, limited canopy data


BC
WA
Seattle
50 km
WA
OR



Funding for lidar acquisition, Winter 2004-2005

$130K	NASA-SENH
$330K	USGS Geography
$400K	Counties, State agencies, Army Corps of Engineers

Total funding, 1999-2005

$0.7M	NASA
$2.0M	add-ons to USGS budget
$0.8M	local sources

psrc.org NASA USGS science for a changing world

Contract specifications and quality assurance

Learning to acquire research-quality lidar data in the commercial sector:

What to ask for?

Have you received what you asked for?

We are learning from experience

- 3 RFP->evaluation->award cycles
- Ongoing client-side data evaluation
  - PSLC and NASA contracts, ~$0.5M data/yr
- Consulting for other lidar clients
  - E.g. San Francisco bay (USGS / CA Coastal Commission), Lake Ozette (Makah Tribe)

What should a lidar contract specify?

- Specifications should be achievable
- Specifications, if met, should guarantee an acceptable product
- Conformance to specifications should be measurable

What to specify:

- Area of coverage
- Date of survey
  - leaf-off, no snow; client approval required
- Instrument capabilities
  - Footprint size. Multiple returns? Intensities? …
- Deliverables
  - Data types (points & attributes, grids, contours, …)
  - Datum, projection, file formats, grid registration
  - Accuracy (slope-dependent: smaller permissible errors in low-slope areas)
  - Completeness
  - Quality of return classification
- Delivery period
- Delivery of points (XYZt) for client approval *before* return classification and surface generation
- Evaluation period
- Protocol to request re-working of data

Quality assurance: 4 steps

1. Are data formally correct?
2. Are data internally consistent?
3. Do data look good?
4. Do data correspond with other observations?

Are data formally correct?

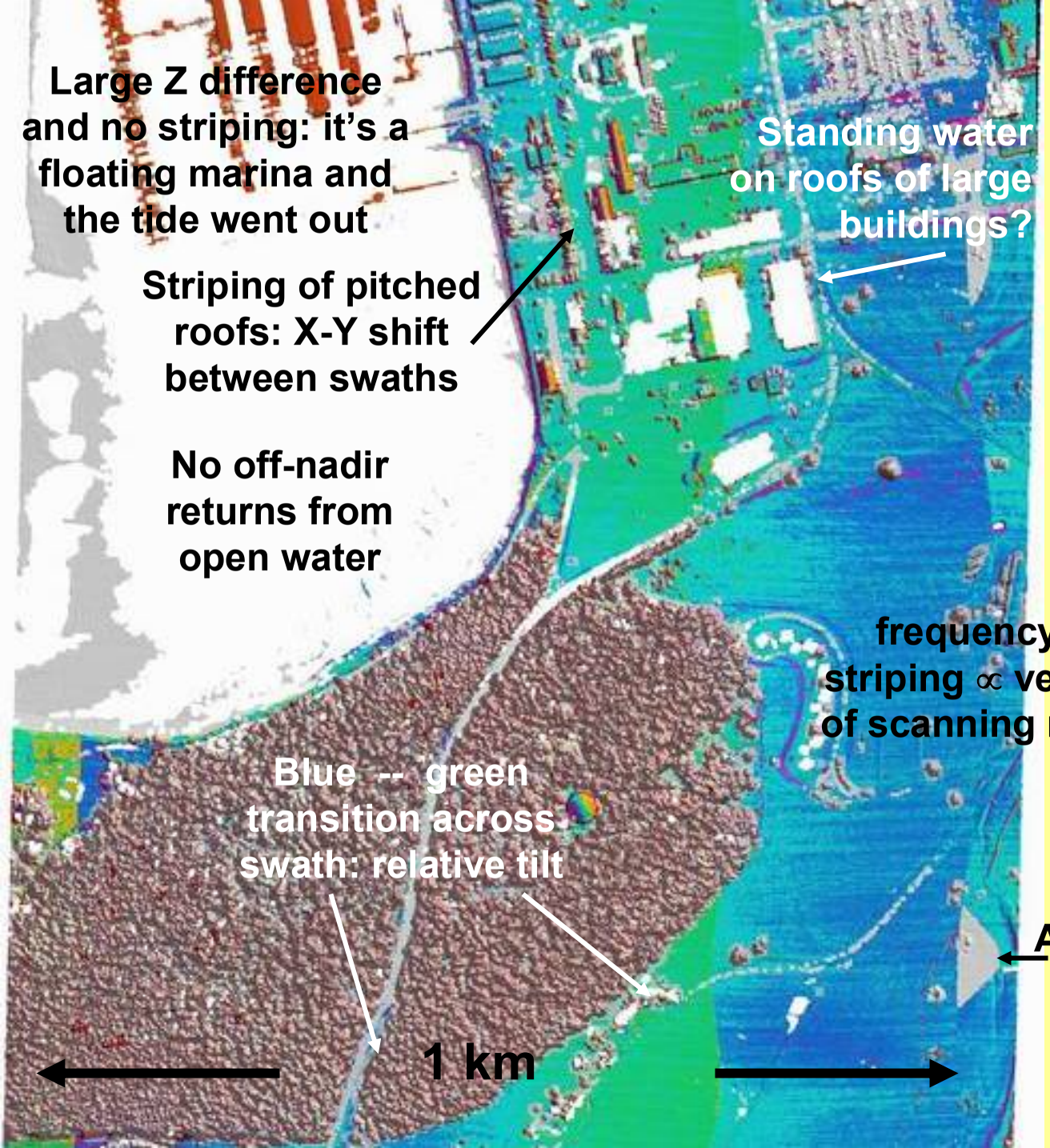
- Read every file. Tabulate:
  - per-file minimum, mean, maximum of each attribute (e.g. Z, time, intensity)
  - abundances of 1st/2nd/3rd/4th returns
  - abundances of Ground/Veg/Structure/Blunder returns
- Typical problems identified:
  - Unreadable media
  - Missing files
  - Inconsistent / incorrect file naming
  - Inconsistent file format
  - Poor classification (too many blunders)
  - Undocumented change in instrument parameters (ratio of 1st / 2nd returns)

Are data internally consistent?

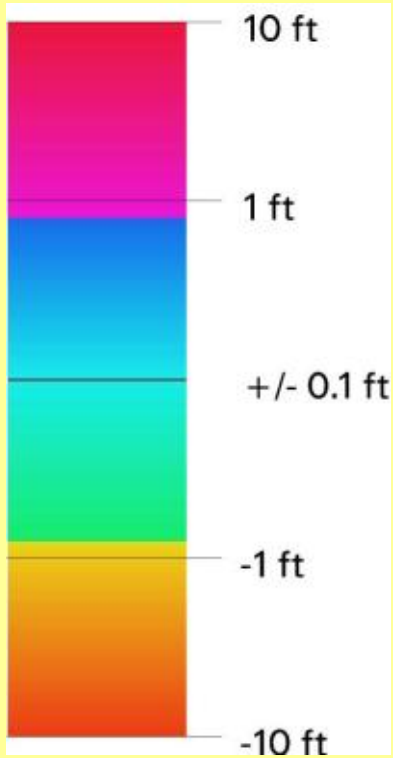
With multiple-return, overlapping swath data:

- Sort points on time. Split into swaths at time breaks. For each swath:
  - Identify data areas
  - Build surface (1st-return points → TIN → lattice)
  - Calculate local curvature to identify areas that should be consistent from swath to swath
- Subtract swath surfaces, merge results
- Make image:
  - Saturated color = low-curvature area with overlap
  - Unsaturated color = high-curvature (canopy) with overlap
  - Gray = no overlap
  - White = no returns

processing is fully automated


Large Z difference and no striping: it's a floating marina and the tide went out
Standing water on roofs of large buildings?
Striping of pitched roofs: X-Y shift between swaths
No off-nadir returns from open water
frequency of striping ∝ velocity of scanning mirror
Blue -- green transition across swath: relative tilt
1 km
Aircraft roll

Difference (Z) between overlapping swaths

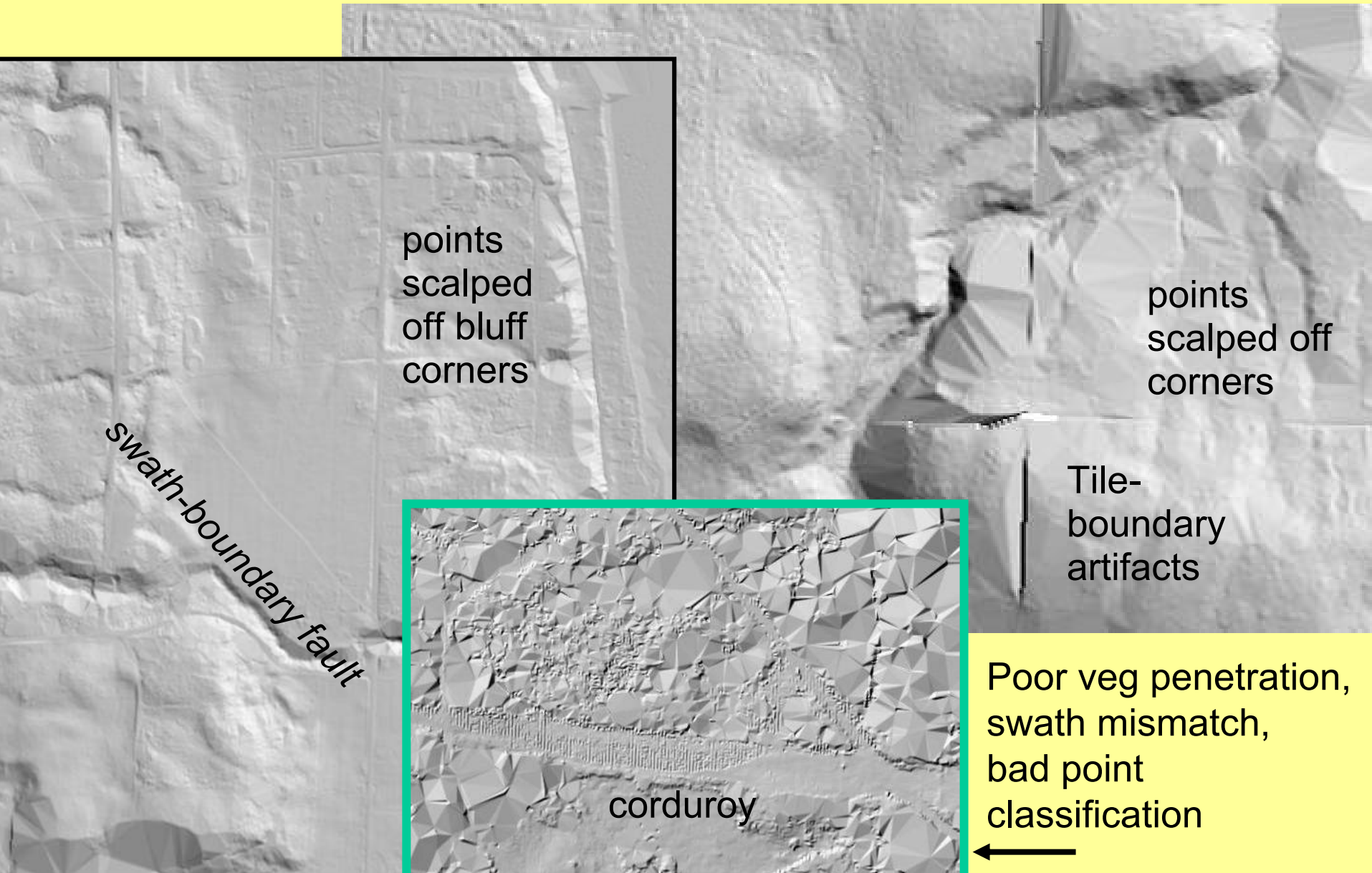


Are data internally consistent? (cont.)

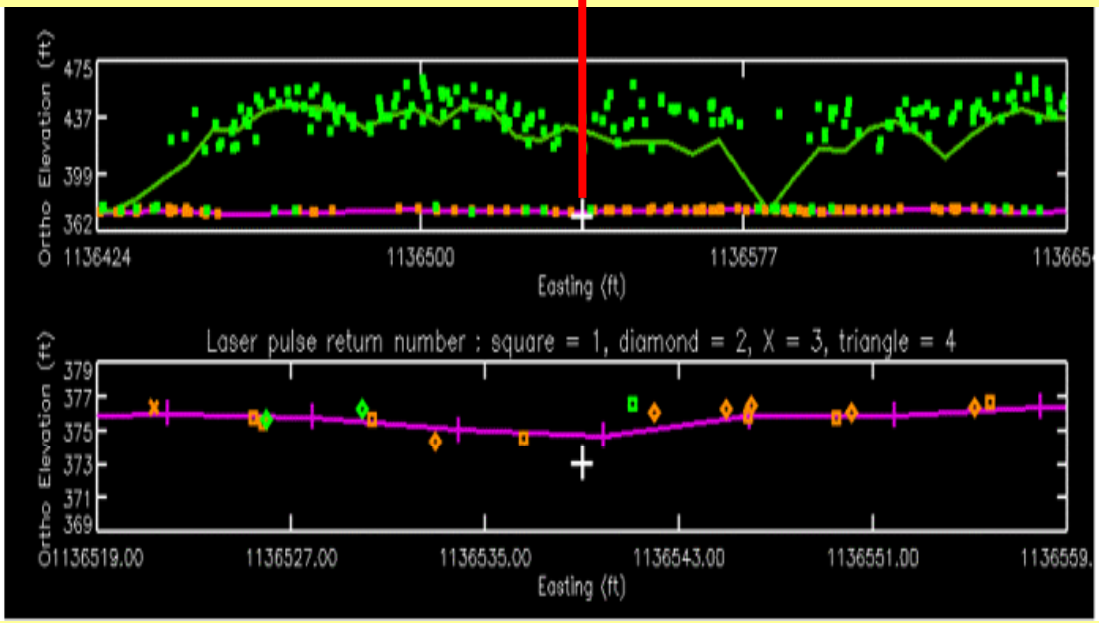
Advantages to this analysis:

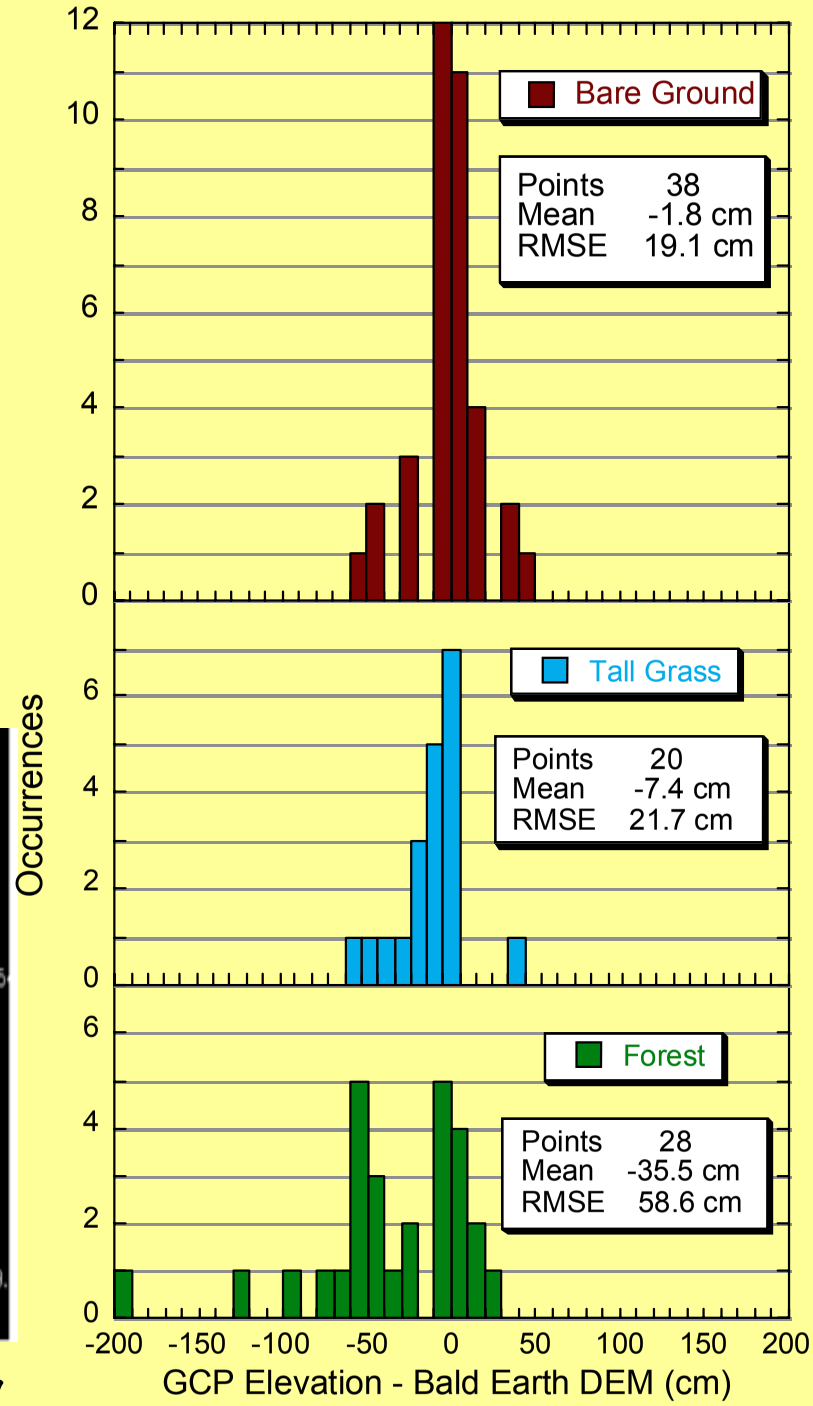
- Insight into performance of lidar system
- Quantitative assessment of completeness
- Robust analysis of vertical measurement error that encompasses most significant sources of error

Do data look good?



Do data correspond with other observations?





GCP analysis of 2000 data

- It is too expensive to obtain enough ground control points (GCPs) to evaluate DEM accuracy across the range of landcover types in a large survey project
- High expense of GCPs is particularly a problem in forested areas
- Testing against GCPs has been valuable primarily to discover incorrectly and (or) inadequately documented survey datums
- We routinely acquire data for large areas with estimated $RMSE_Z$ = 5-10 cm on low-slope surfaces

Unsolved challenges in contract specifications and quality assurance

- Contract language for completeness (e.g. sidelap, point density, absence of holidays)
  - What variation is permissible?
- Contract language for permissible distributions of errors (in magnitude, in space)
  - What distributions are reasonable and permissible?
  - How do we describe spatial distribution of errors?

Unsolved challenges in contract specifications and quality assurance

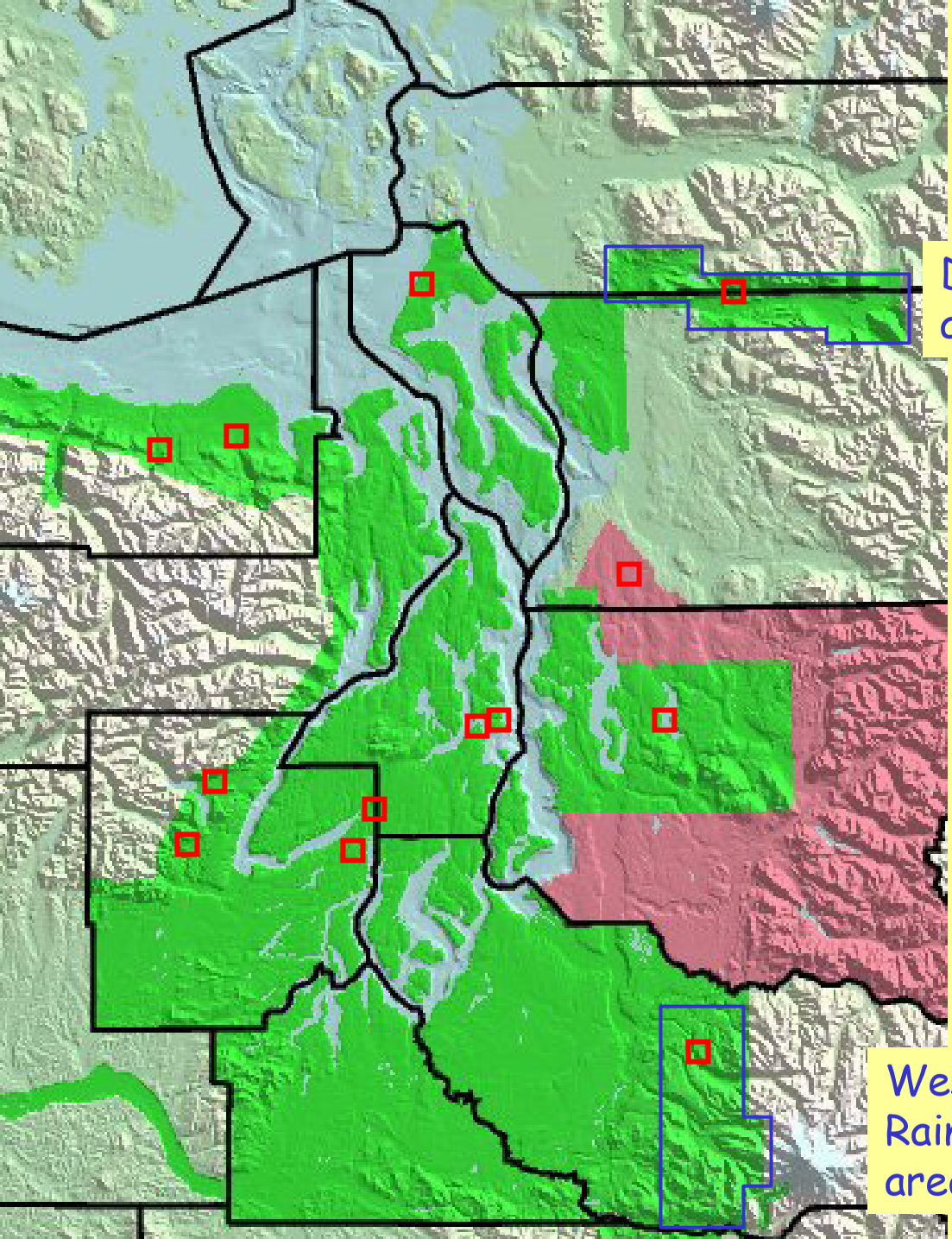
- Quantitative measure of classification accuracy
  - Lack an external standard
- Swath-to-swath consistency analysis for internal estimate of bare-earth DEM accuracy
  - What constitutes a no-data area?

Using high-resolution lidar topography in natural hazards studies

1. Fault scarp inventory
2. Geomorphic mapping
3. Topographic change at Mount St Helens

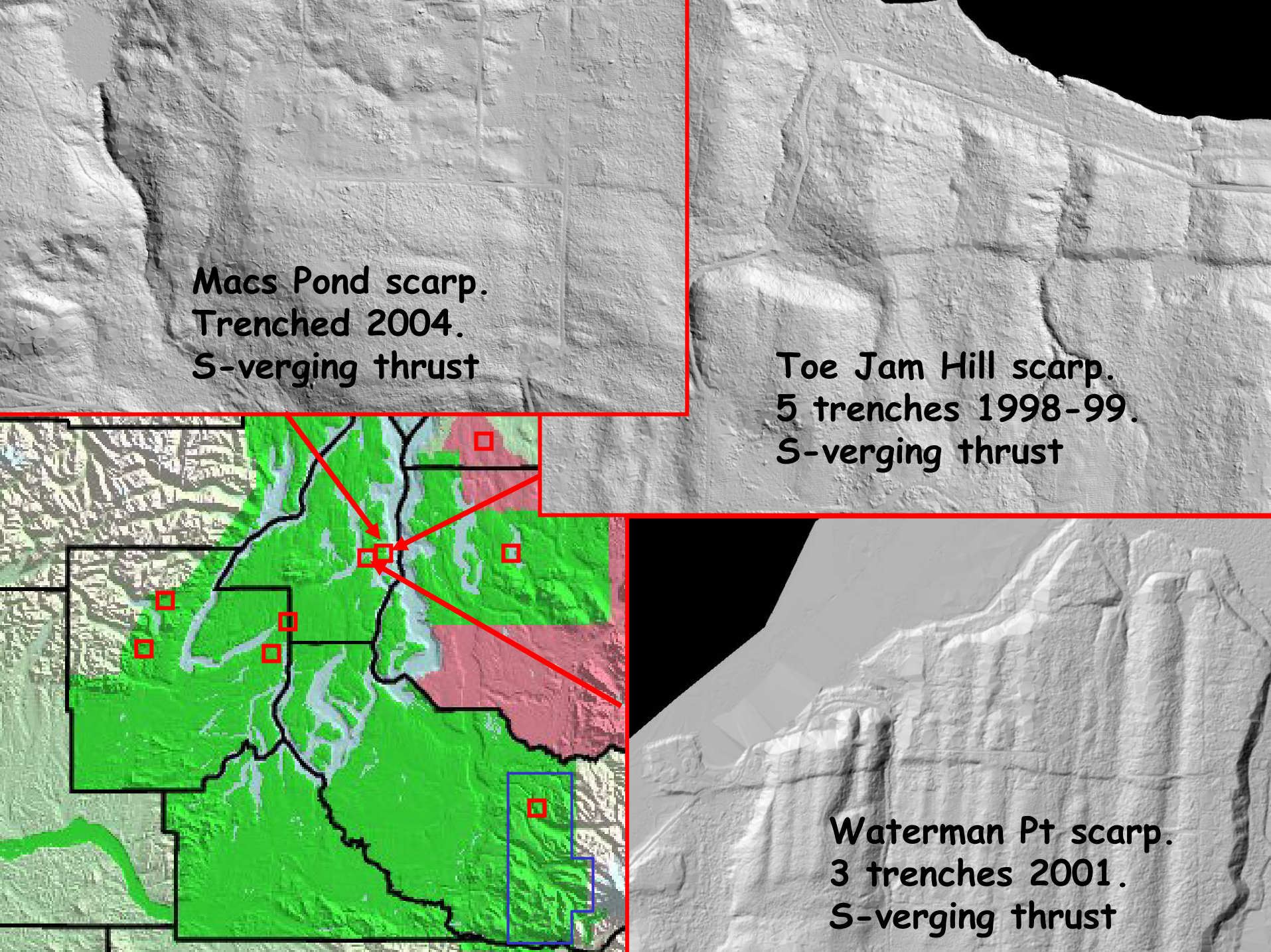
Fault scarp inventory

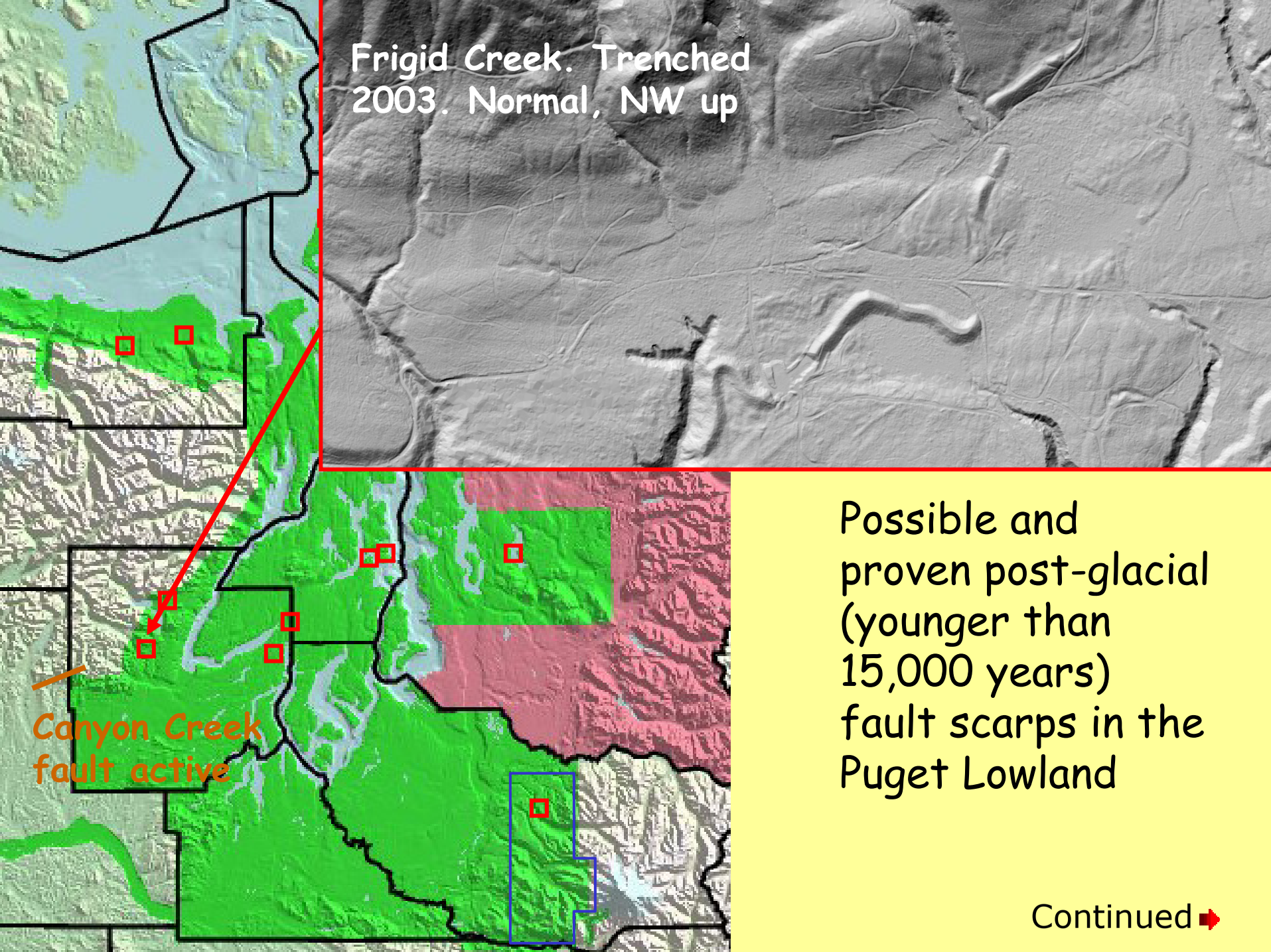
- Paleoseismologists excavate scarps to establish recurrence intervals for earthquakes on crustal faults
- Prior to 1997, young fault scarps recognized at only one location in western Washington
- With high-resolution lidar topography we have since identified more than a dozen additional scarps of probable tectonic origin
- Scarps identified in recently acquired data (West Rainier, Darrington) have not yet been excavated



Possible and proven post-glacial (younger than 15,000 years) fault scarps in the Puget Lowland

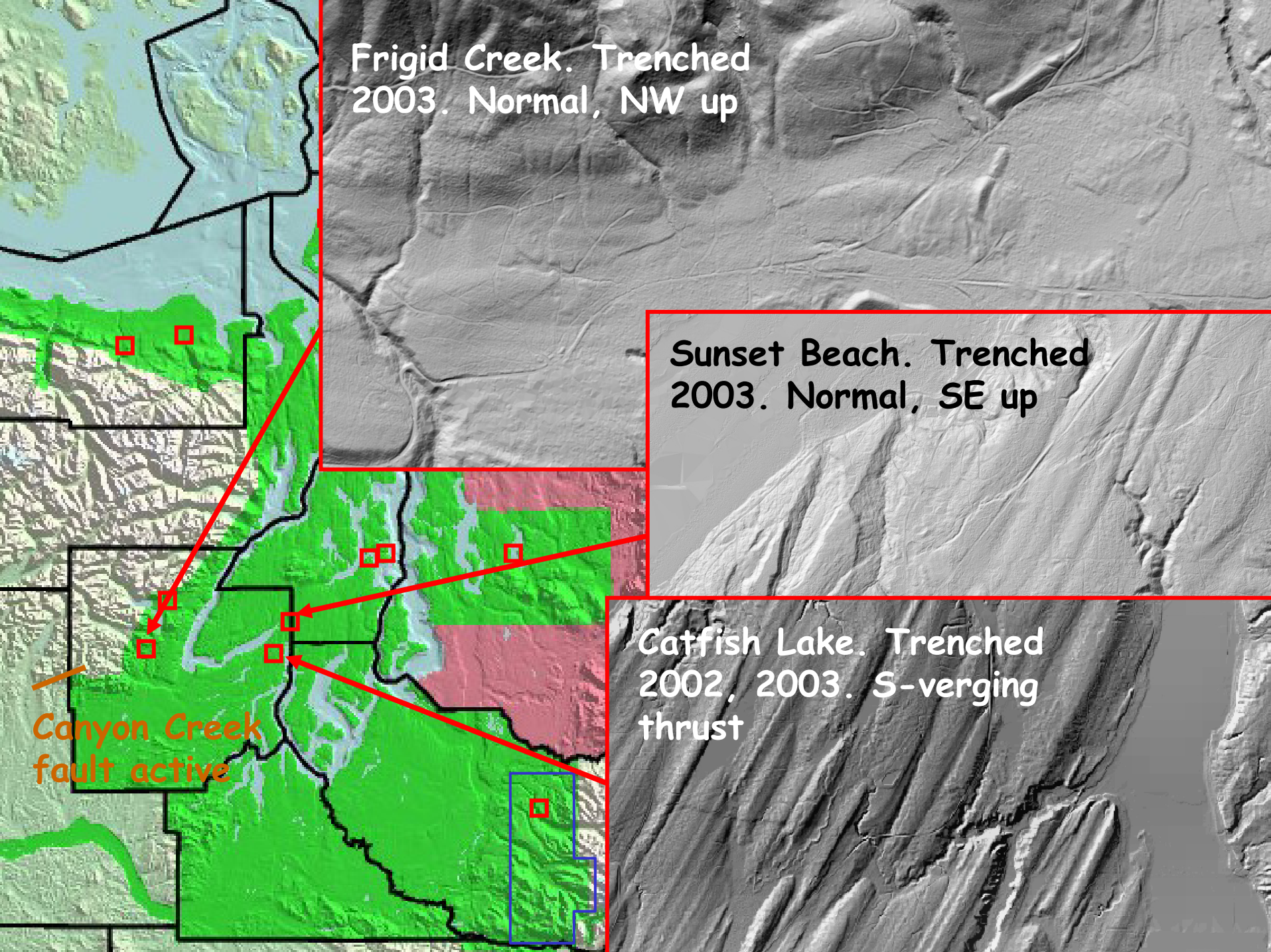
Continued

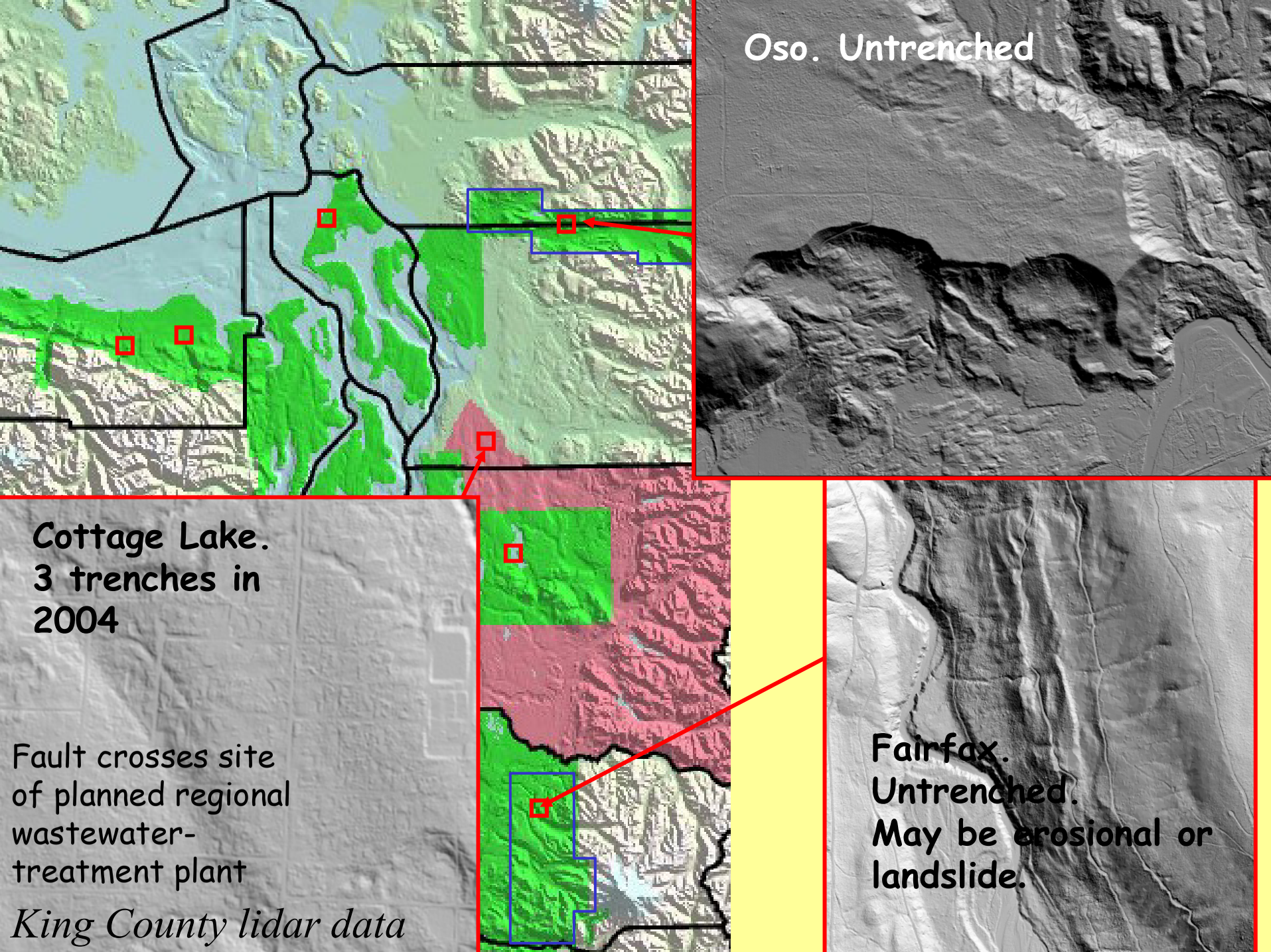

Macs Pond scarp.
Trenched 2004.
S-verging thrust
Toe Jam Hill scarp.
5 trenches 1998-99.
S-verging thrust
Waterman Pt scarp.
3 trenches 2001.
S-verging thrust

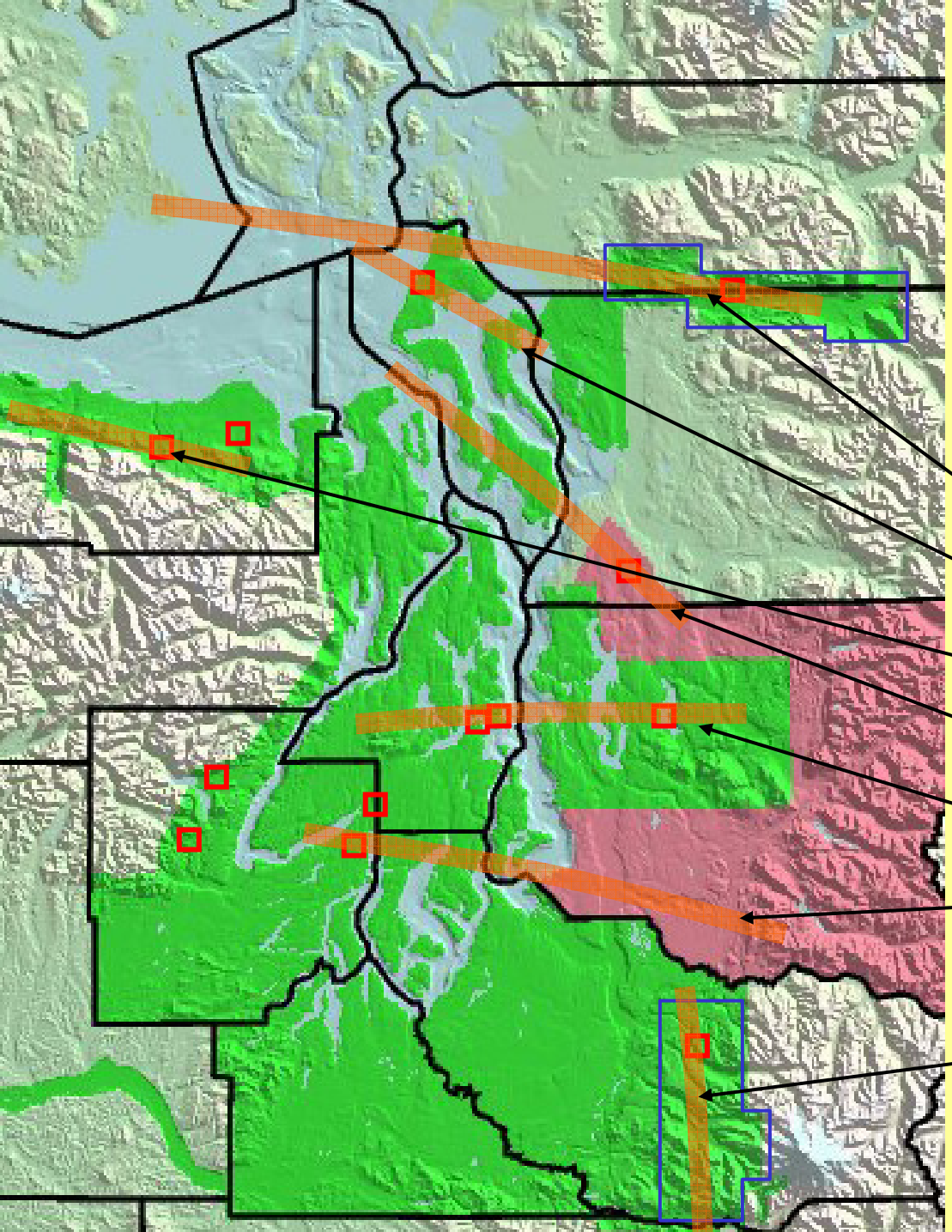


Possible and proven post-glacial (younger than 15,000 years) fault scarps in the Puget Lowland

Continued


Frigid Creek. Trenched 2003. Normal, NW up
Sunset Beach. Trenched 2003. Normal, SE up
Catfish Lake. Trenched 2002, 2003. S-verging thrust
Canyon Creek fault active


Oso. Untrenched
Cottage Lake.
3 trenches in
2004
Fault crosses site
of planned regional
wastewater-
treatment plant
King County lidar data
Fairfax.
Untrenched.
May be erosional or
landslide.



Most new-found fault scarps are on previously recognized faults.

Some are not.

Devils Mtn fault

Utsalady Point fault

Little River fault

S Whidbey Island fault

Seattle fault

Tacoma (White River) fault

West Rainier seismic zone

Geomorphic mapping

Questions

How was Puget Lowland landscape formed?

How much has it deformed?

Method

Map surface units, not features

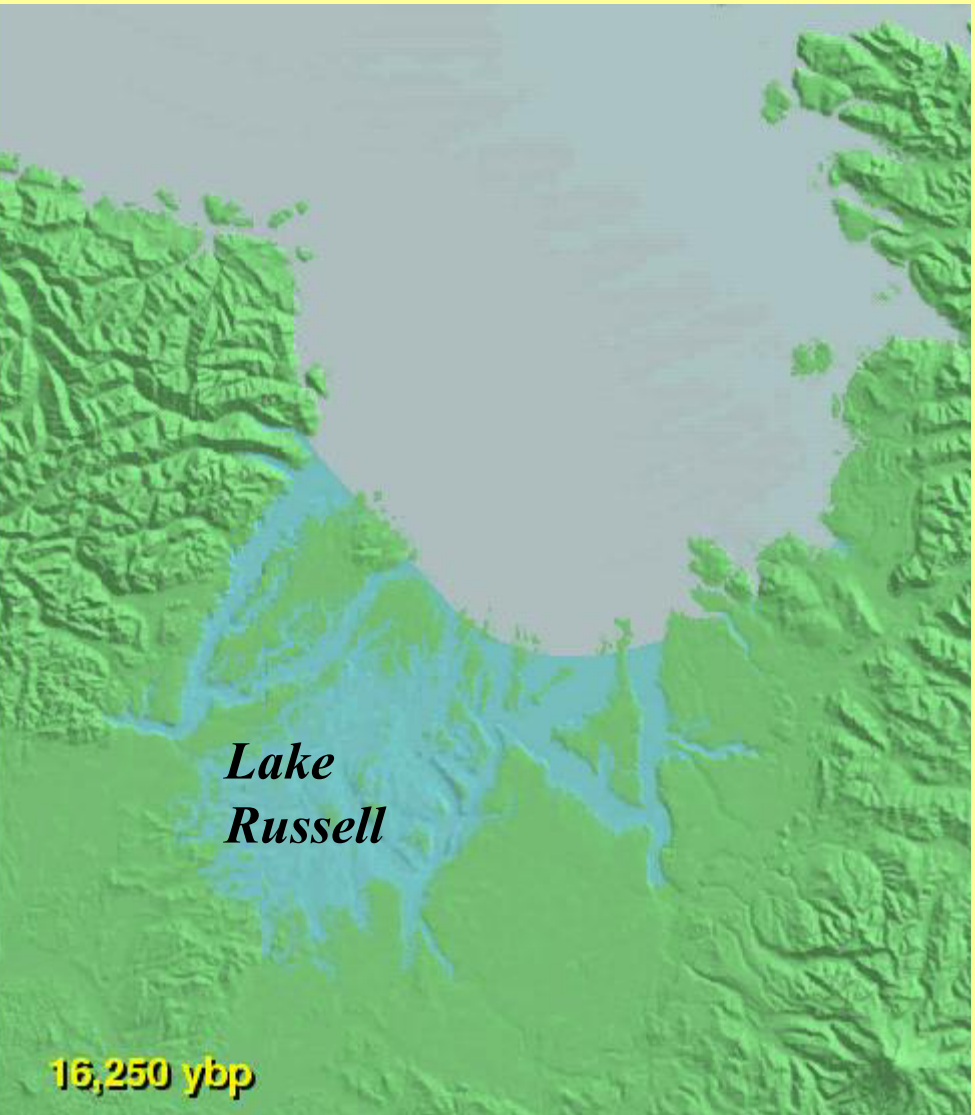
Units induced from observations, not deduced from geomorphic theory

Units defined on basis of

1) texture and position

2) inferred genesis

3) age



At end of last glaciation, retreating Cordilleran ice sheet dammed large periglacial lakes in the Puget Lowland

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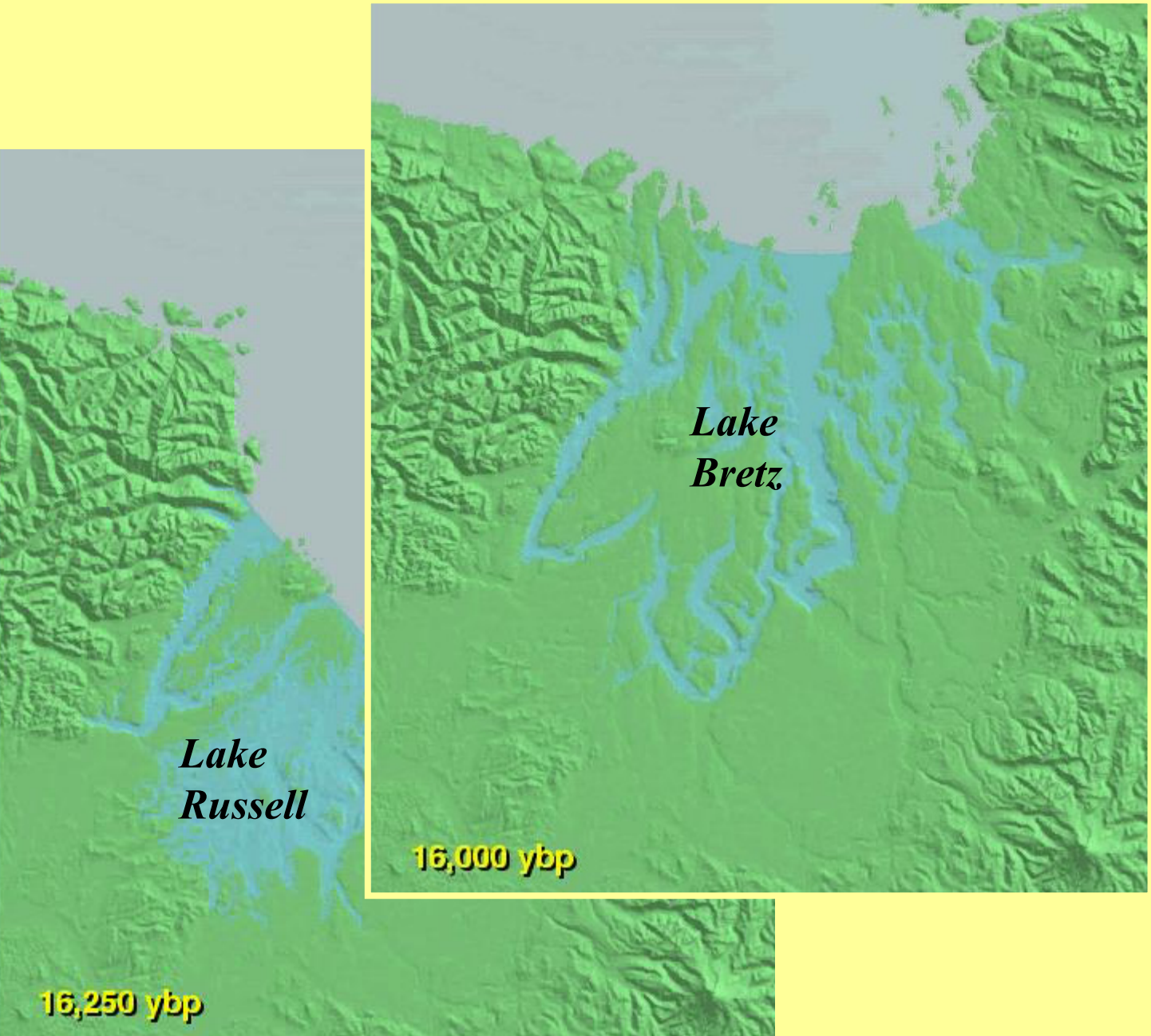

: glaciation,
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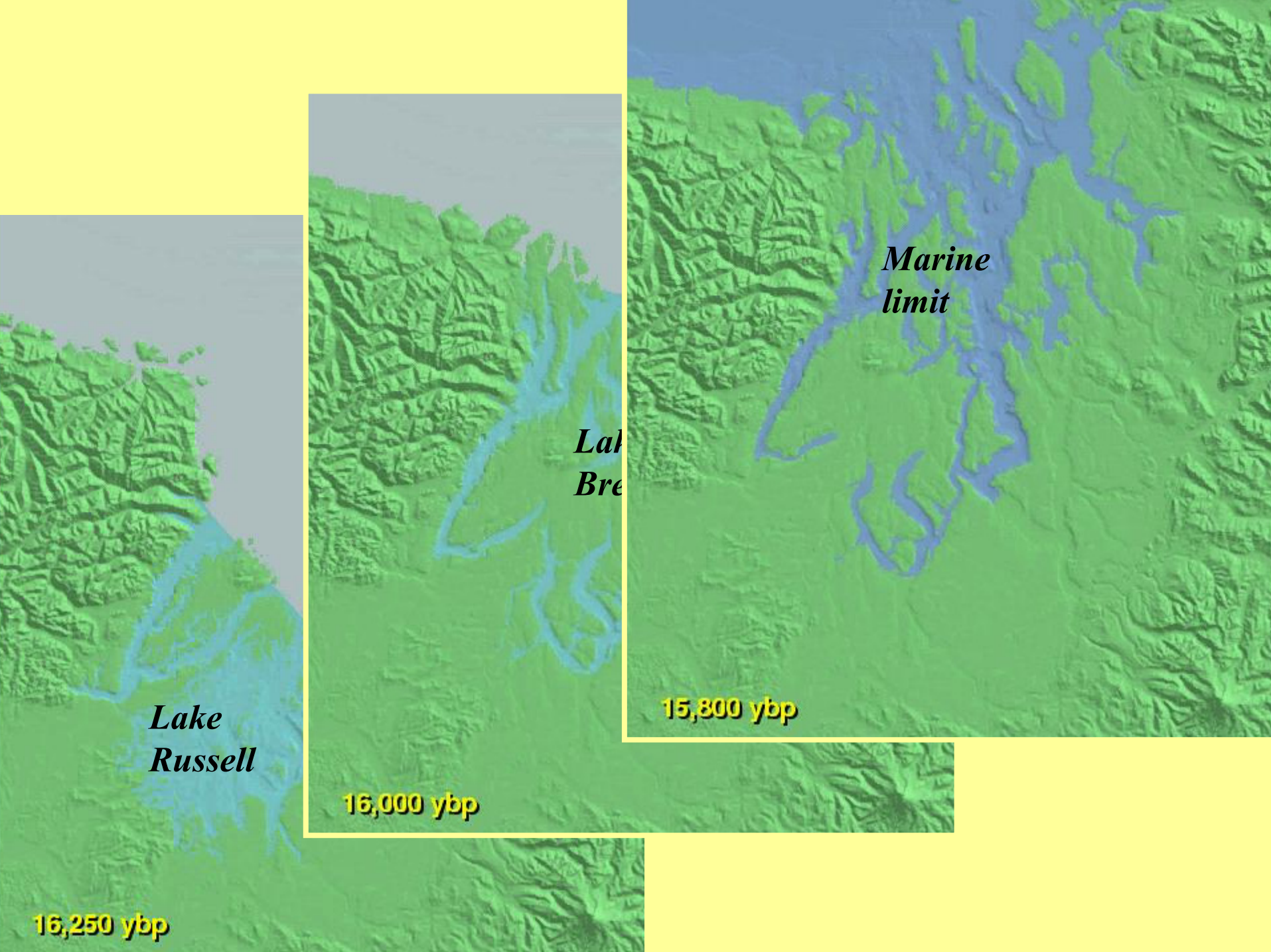
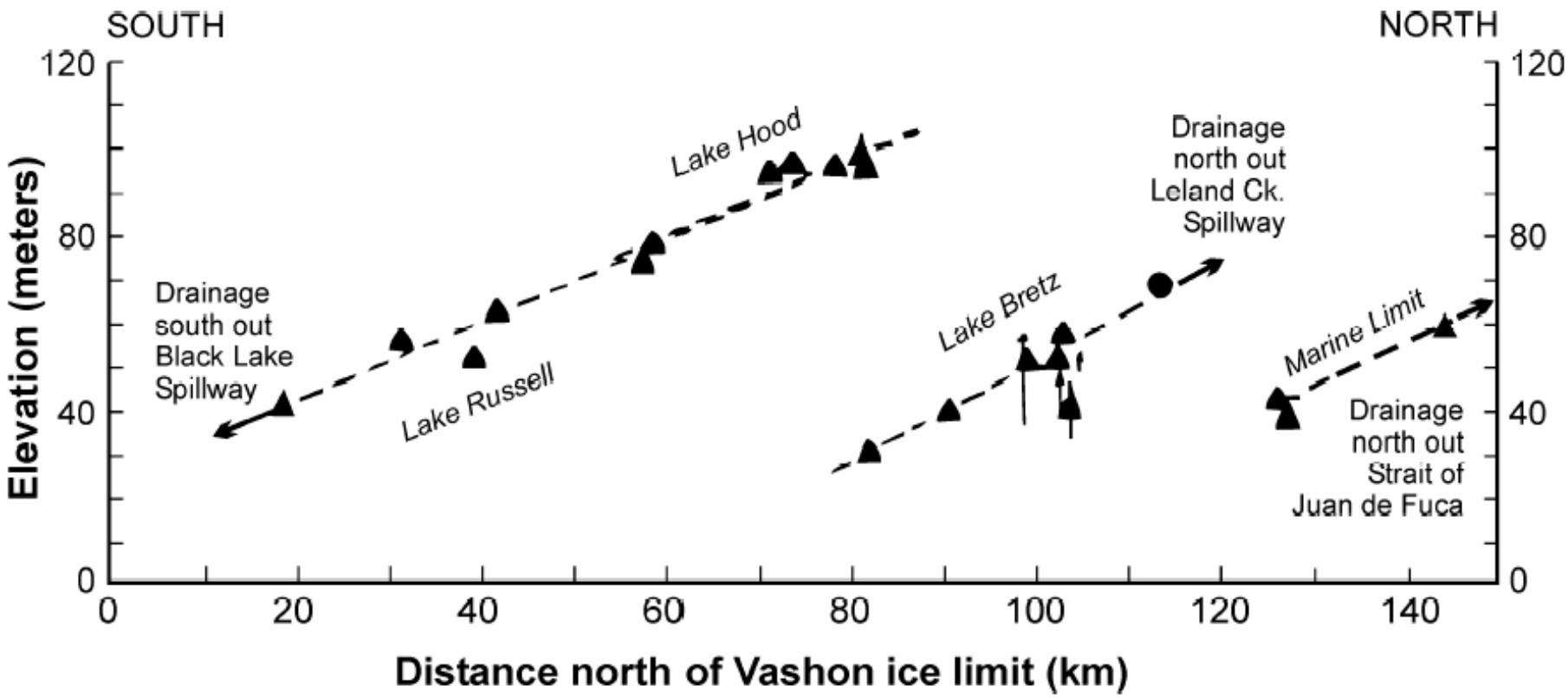

Marine
limit
15,800 ybp
Lak
Bre
16,000 ybp
Lake
Russell
16,250 ybp

Glacio-isostatic rebound of Puget Lowland documented from displaced deltas by Thorson (1989) and Dethier and others (1995)



from Booth and others, 2004

lakes at the site of Puget Sound about
16,000 years ago (4), I reconstructed a domal pattern of postglacial uplift dominat-

and nearly perpendicular to the fault trace. I then subdivided the data set into three

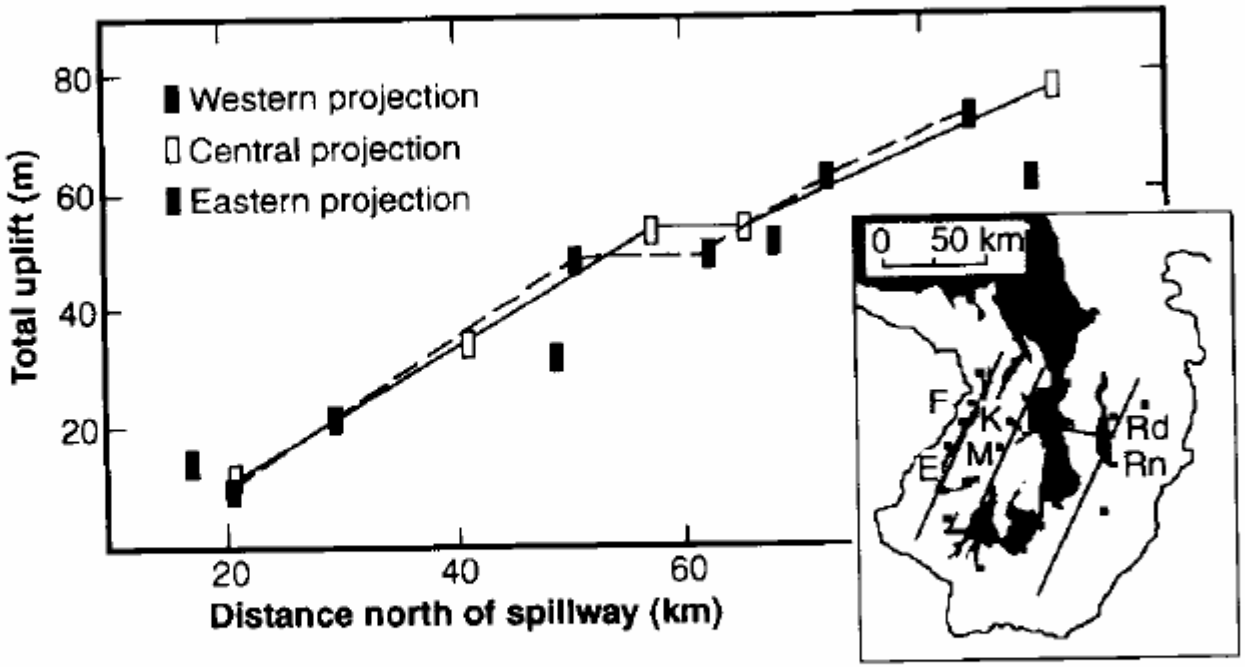


Fig. 1. Net uplift of glaciolacustrine deltas relative to the lake outlet for three parallel projections. Location of deltas (F, Fulton Creek; E, Eldon; K, Kitsap Lake; M, McKenna Falls; Rd, Redmond; and Rn, Renton) and the trace of the Seattle fault (northwest-trending line) are shown on inset map.

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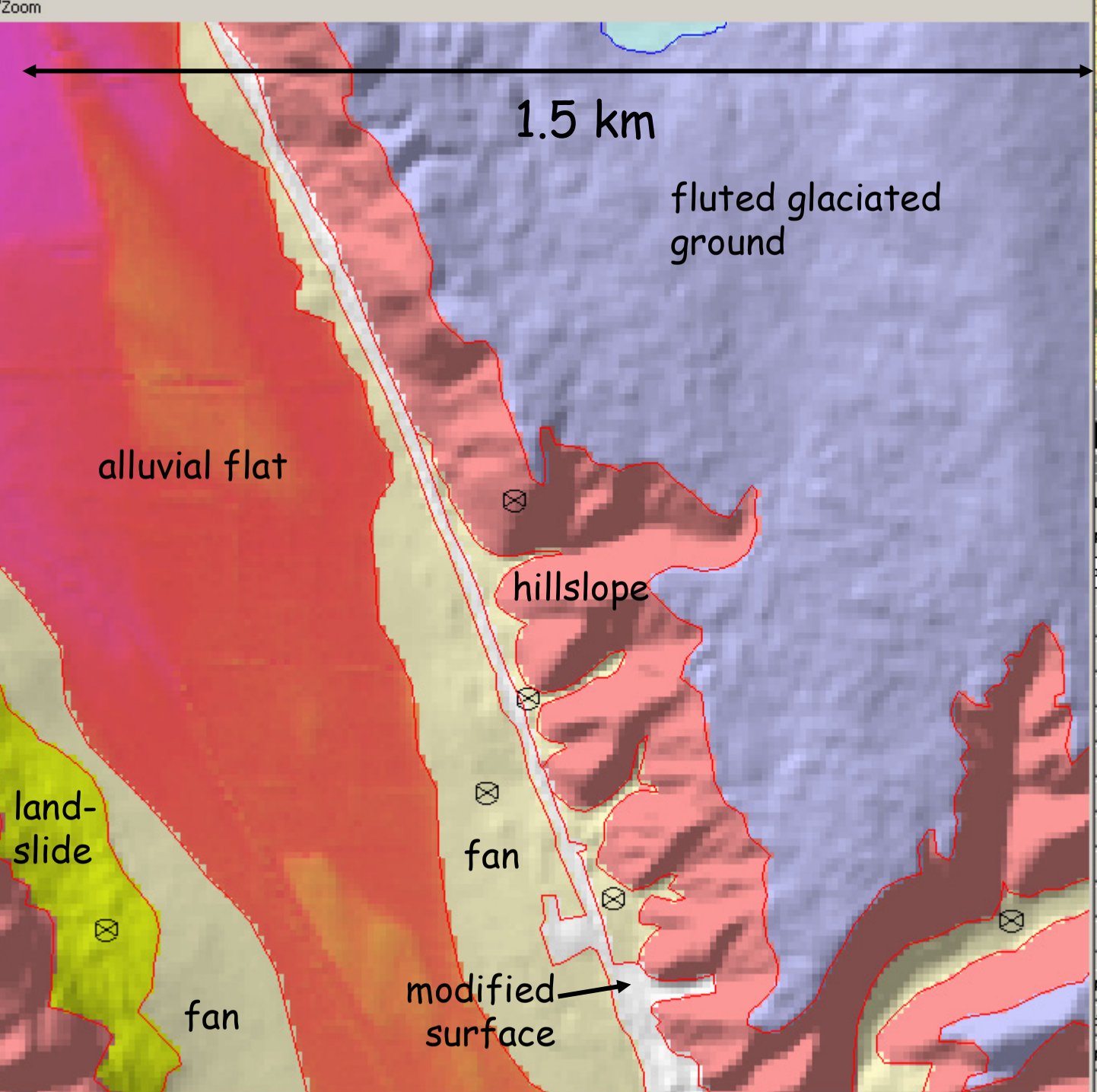
Late-glacial paleohorizontals disclose (and limit) Holocene tectonism?

from Thorson, 1993



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glacier bdr
swamp bdry

CONTACTS & FAULTS

URCE ejc_.tif

ALE 6900 RESET

ntact

ADD

ADD-RESEL DANGLE-DELETE

SEL MANY-DELETE SEL POLY PASST

SEL MANY CALC LTYP

SEL ONE-SPLIT SEL MANY-

SEL ONE-VERTEX MOVE SEL MAN

SET PRECISION SEL MAN

MOVE NODES SEL MANY-I

OOPS REDRAW

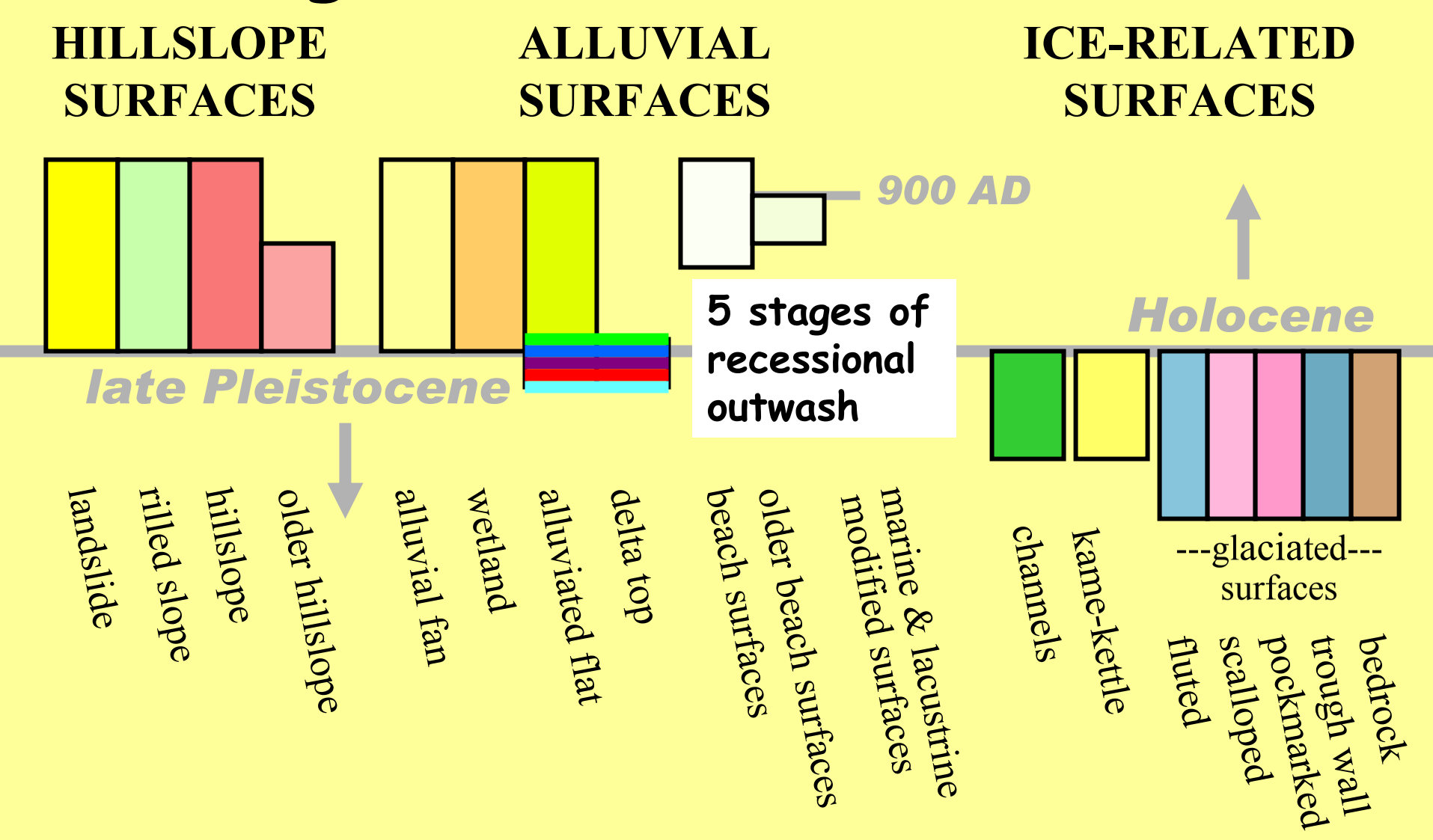
SEL POLY - SMOOTH

AVE CHANGE DRAW SET

dit CHANGE BACKDROP

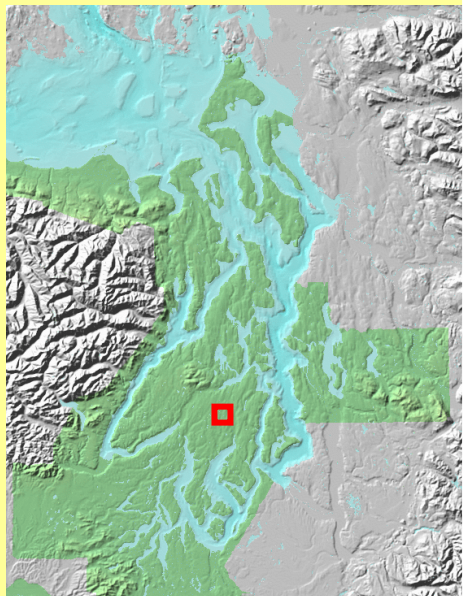
AVE-QUIT QUIT

Geomorphic "stratigraphy" of the Puget Lowland

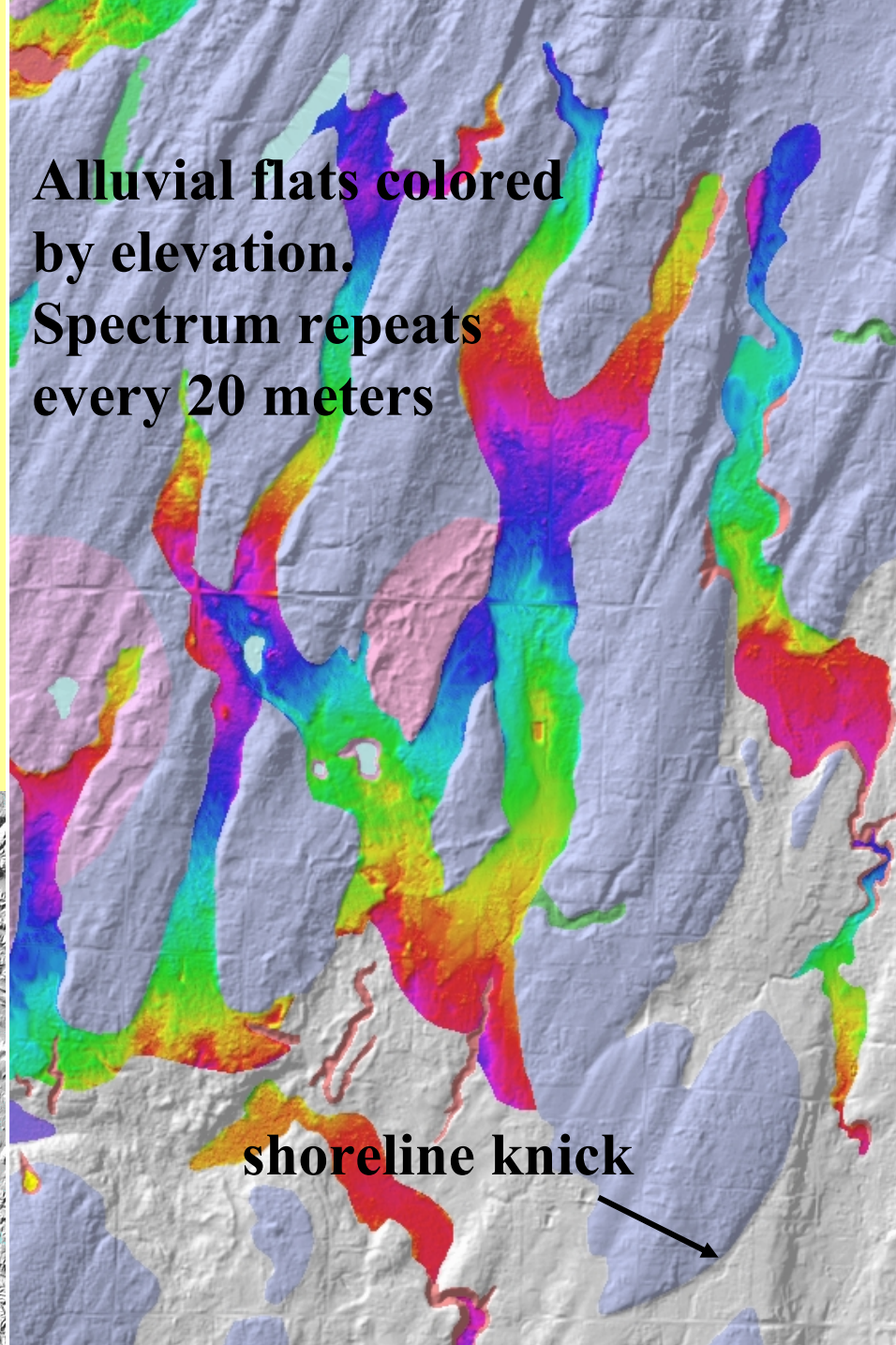


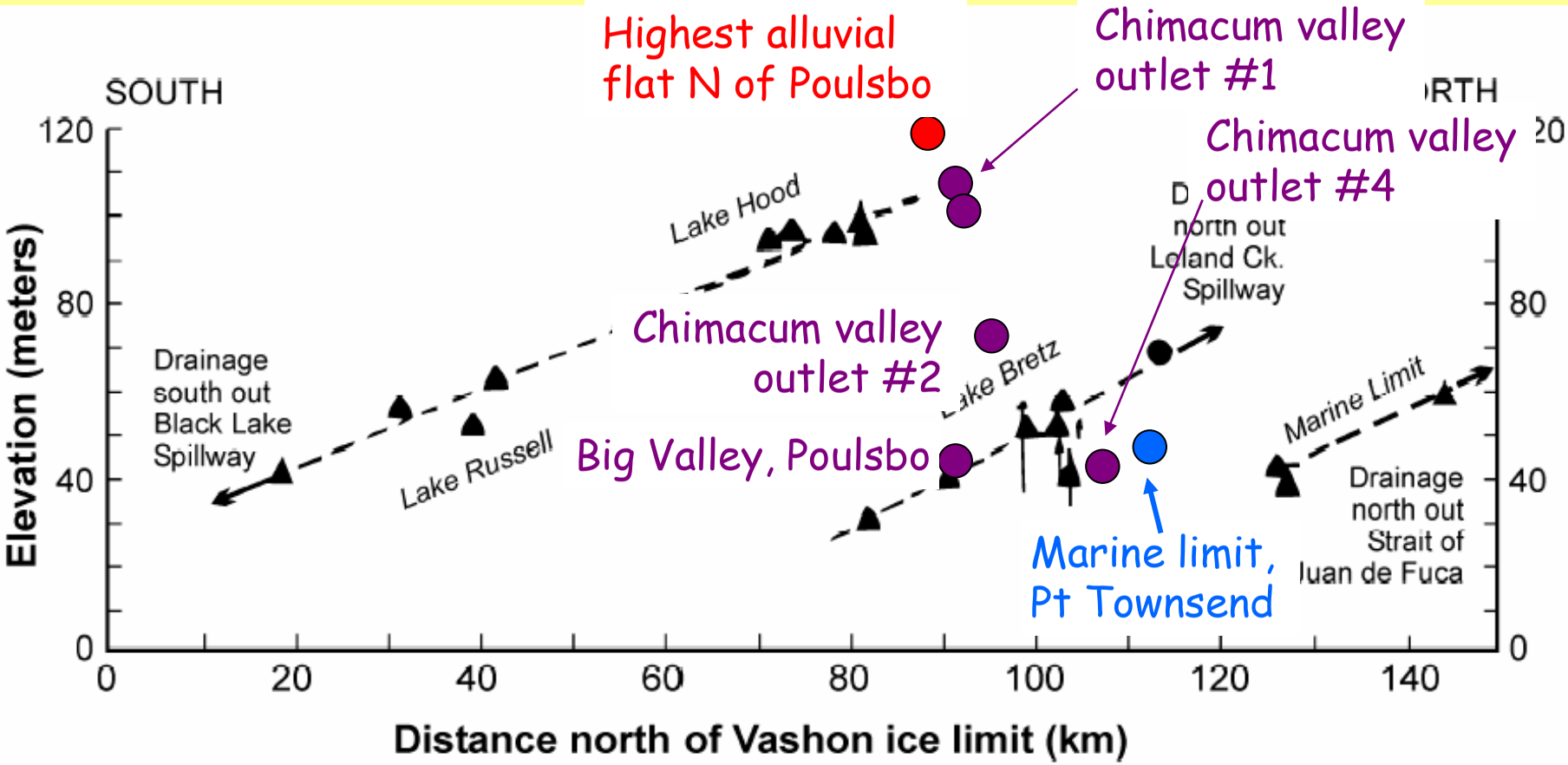
High-elevation alluvial and lacustrine-modified surfaces at appropriate elevation for Lake Russell

← 5 km →



Requires ice margin near heads of alluvial flats



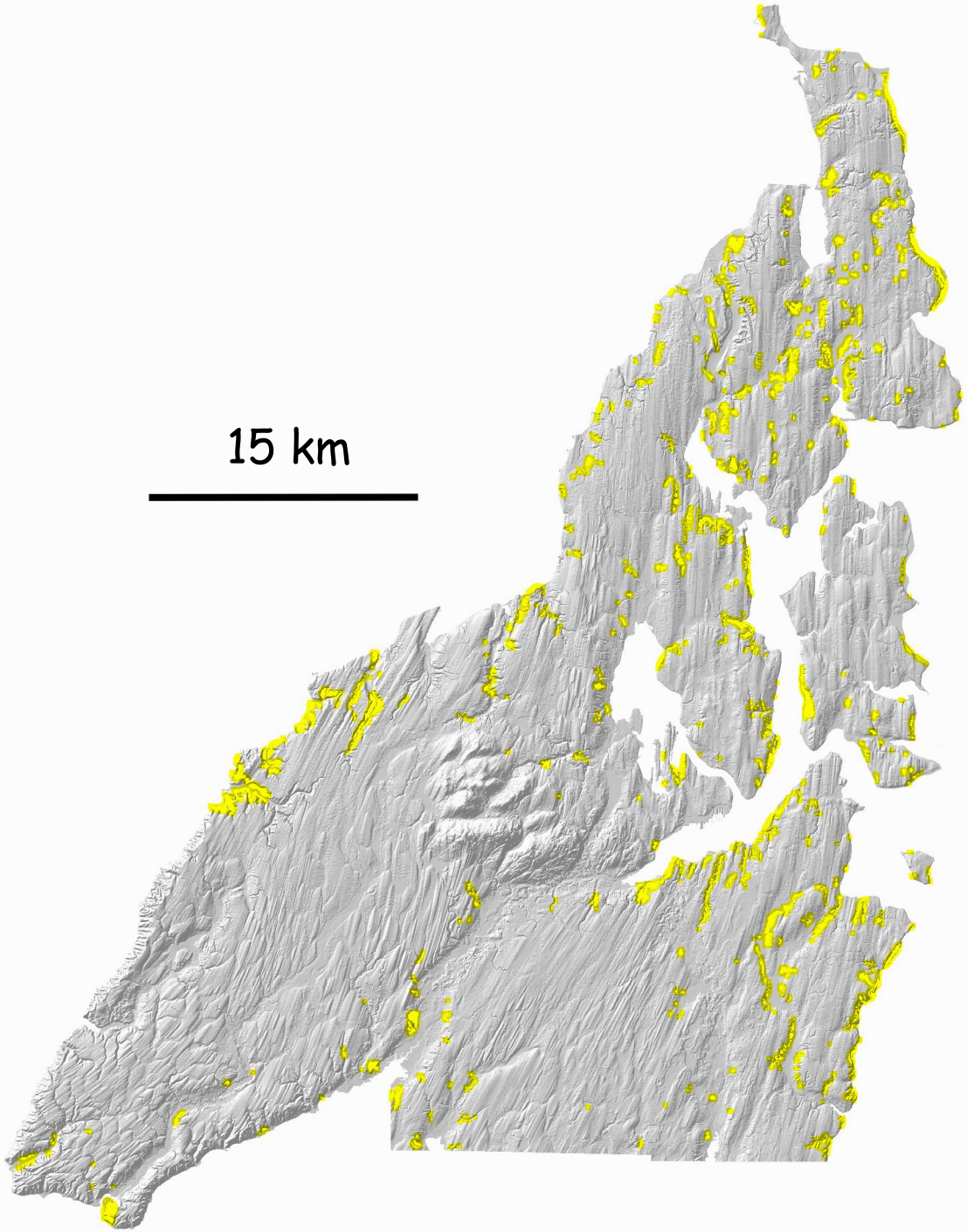

Highest alluvial flat N of Poulsbo
Chimacum valley outlet #1
Chimacum valley outlet #4
Chimacum valley outlet #2
Big Valley, Poulsbo
Marine limit, Pt Townsend
SOUTH
RTH
Lake Hood
Lake Russell
Lake Bretz
Drainage south out Black Lake Spillway
D
nortn out
Leland Ck.
Spillway
Marine Limit
Drainage north out Strait of Juan de Fuca
Elevation (meters)
Distance north of Vashon ice limit (km)
0
40
80
120
0
20
40
60
80
100
120
140

Landslides

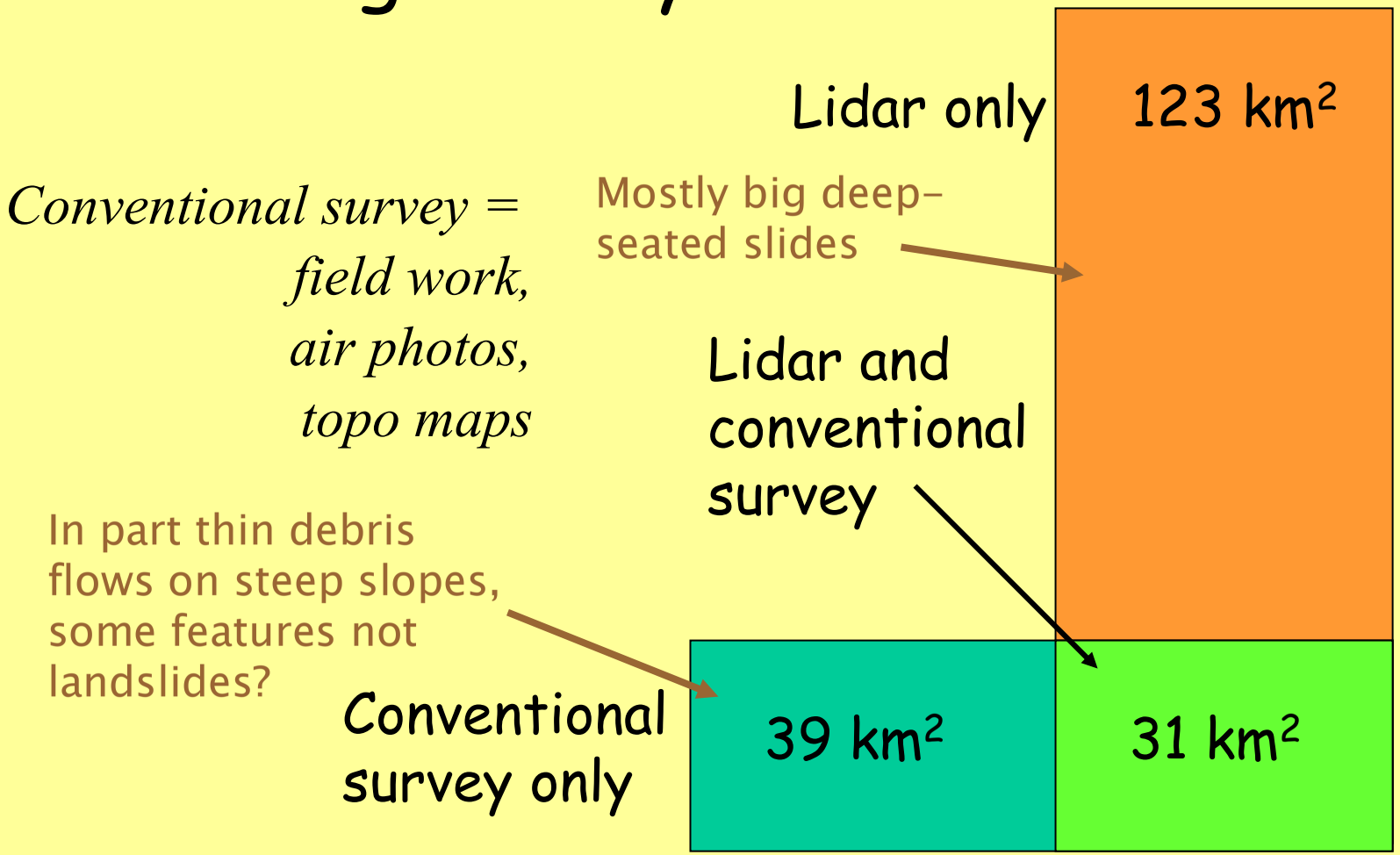
extracted from geomorphic map of Kitsap Peninsula; estimated positional accuracy ± 5m

Rich, consistent inventory of deep-seated landslides.

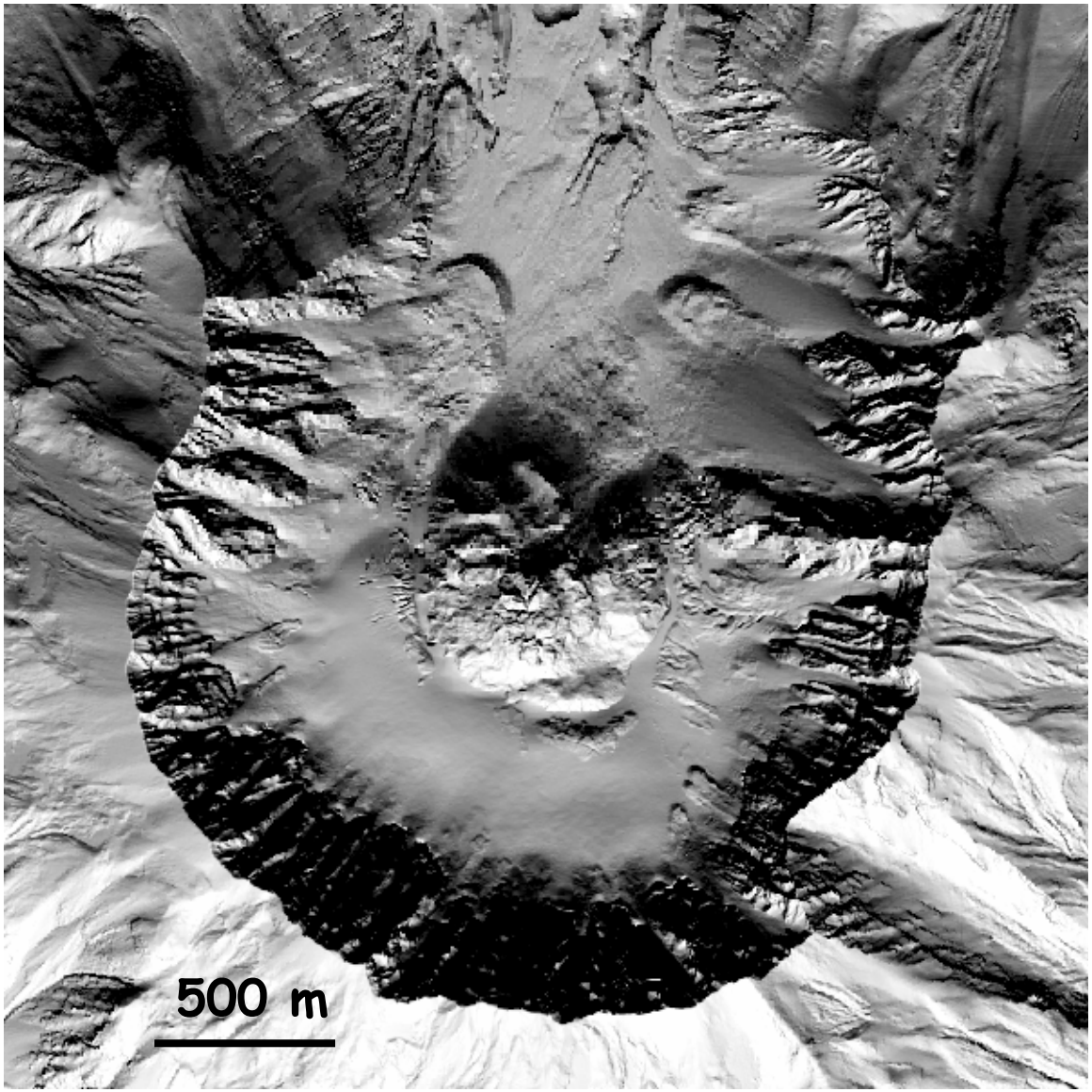
Cannot map shallow debris flows; can map hillslopes on which they have been generated



Comparison of conventional and lidar landslide inventories, central King County


Lidar only
123 km²
Conventional survey = field work, air photos, topo maps
Mostly big deep-seated slides
Lidar and conventional survey
In part thin debris flows on steep slopes, some features not landslides?
Conventional survey only
39 km²
31 km²

Topographic change at Mount St Helens



September, 2003

September 2003

USGS-funded lidar survey, EarthData

September 23, 2004

Seismicity steps up

September 24

speculative lidar survey, Watershed Sciences

September 26

1st uplift observed

September 30

speculative lidar survey, Watershed Sciences

October 4

NASA-funded lidar survey, TerraPoint

October 14

USGS-NASA funded lidar survey, Watershed Sciences

November 20

NASA-funded lidar survey, TerraPoint

- September 03 survey is minimally documented
- Where is GPS base station JRO1? (ITRF2000 *vs* NAD83)
  - multiple estimates of ~1.5 m difference
- 9-24 and 9-30 surveys with 0.03 Hz GPS!
- No *in-situ* GPS for calibration and ground control after 9-23-04 onset of seismicity
  - existing ground control may have mixed datums
- 9-24, 9-30, and 10-14 surveys with new, unproven instrument

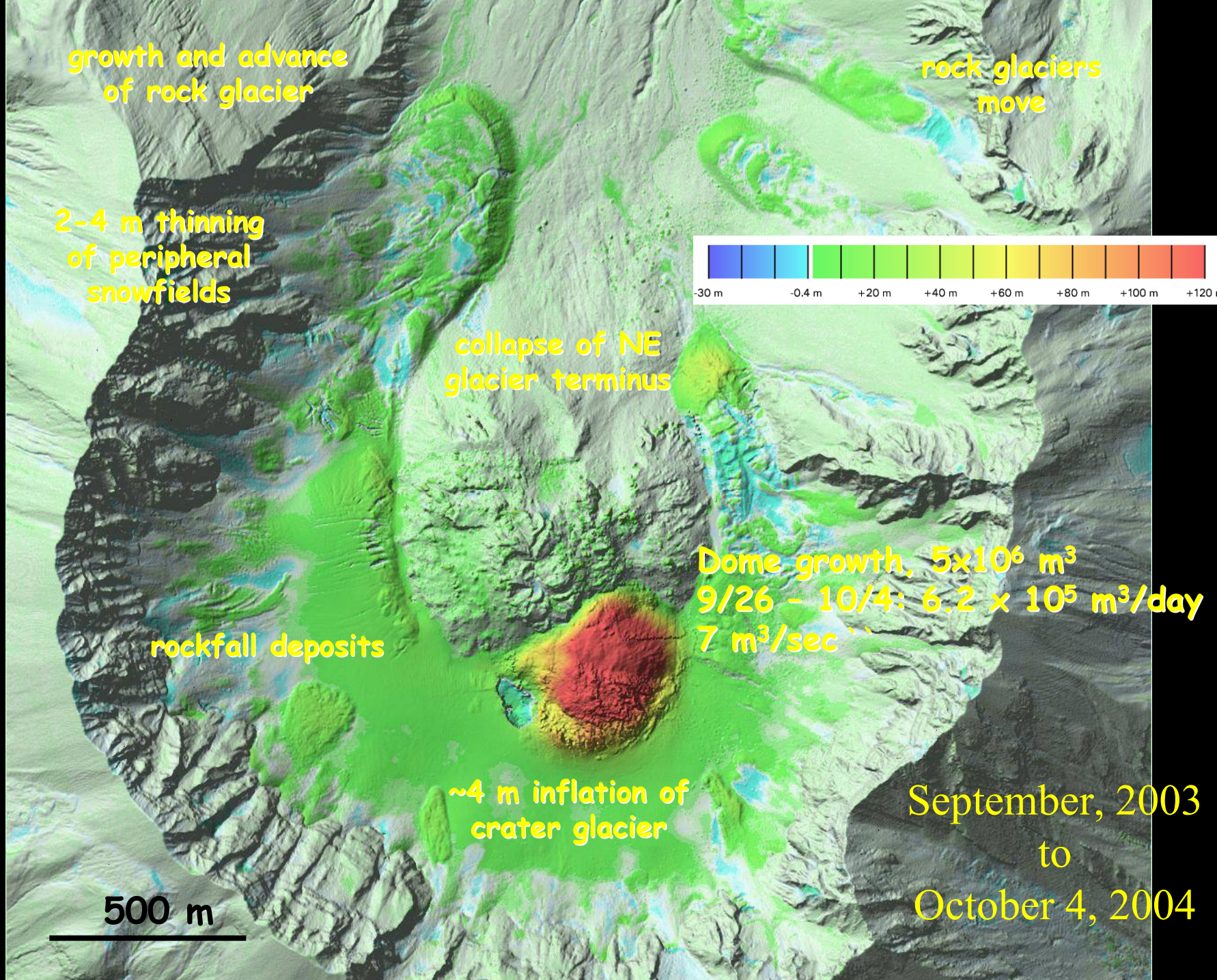
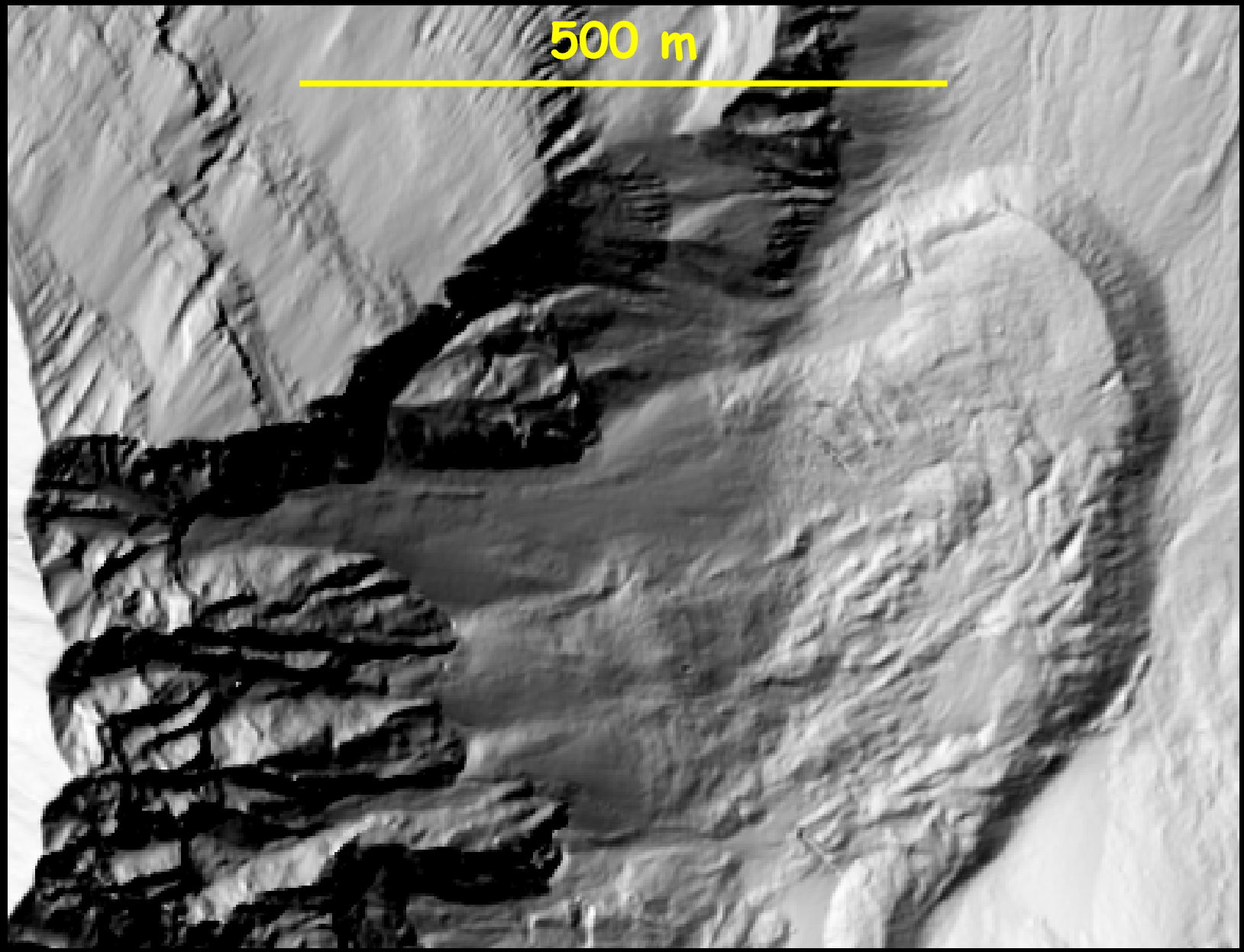
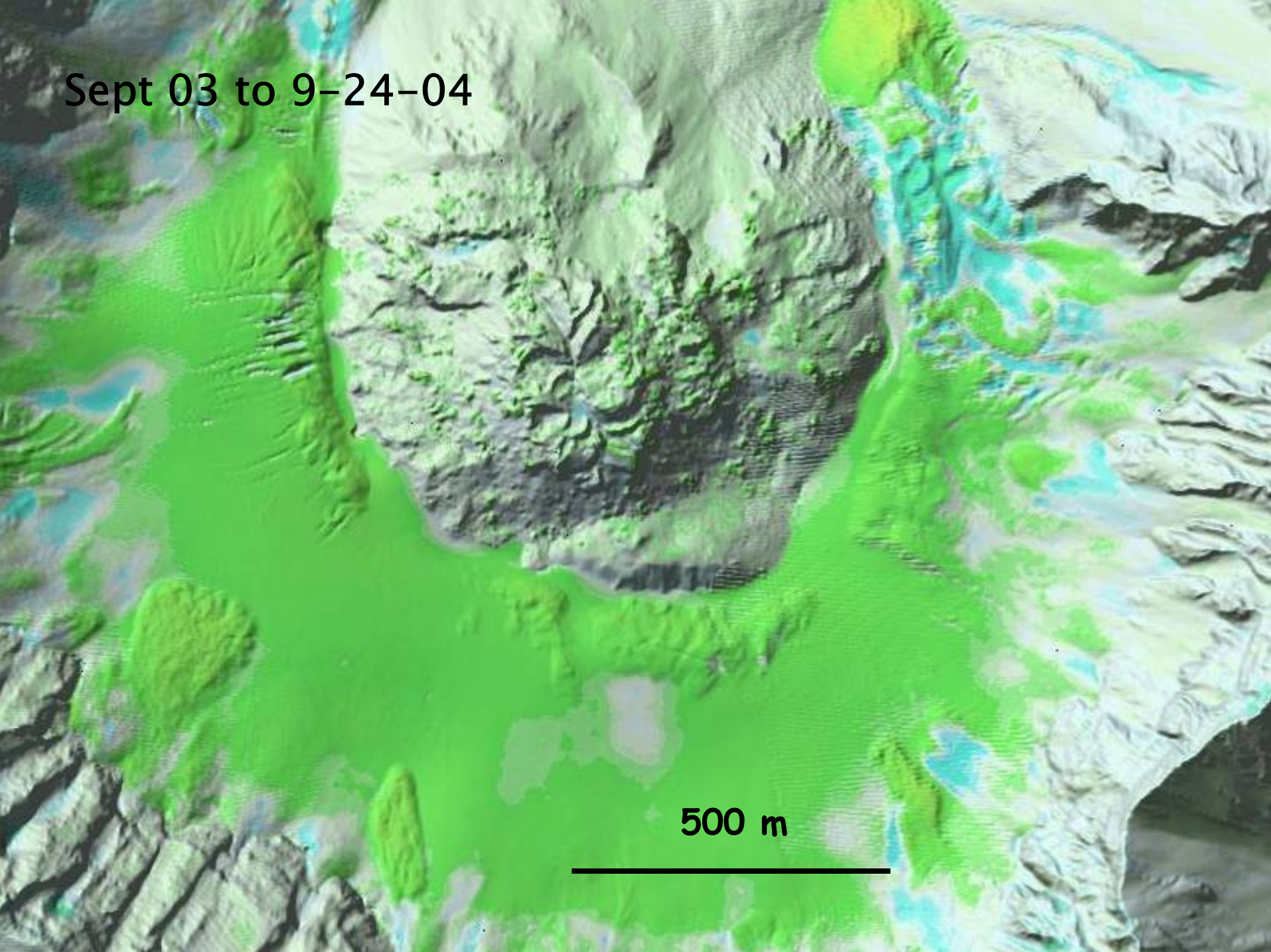
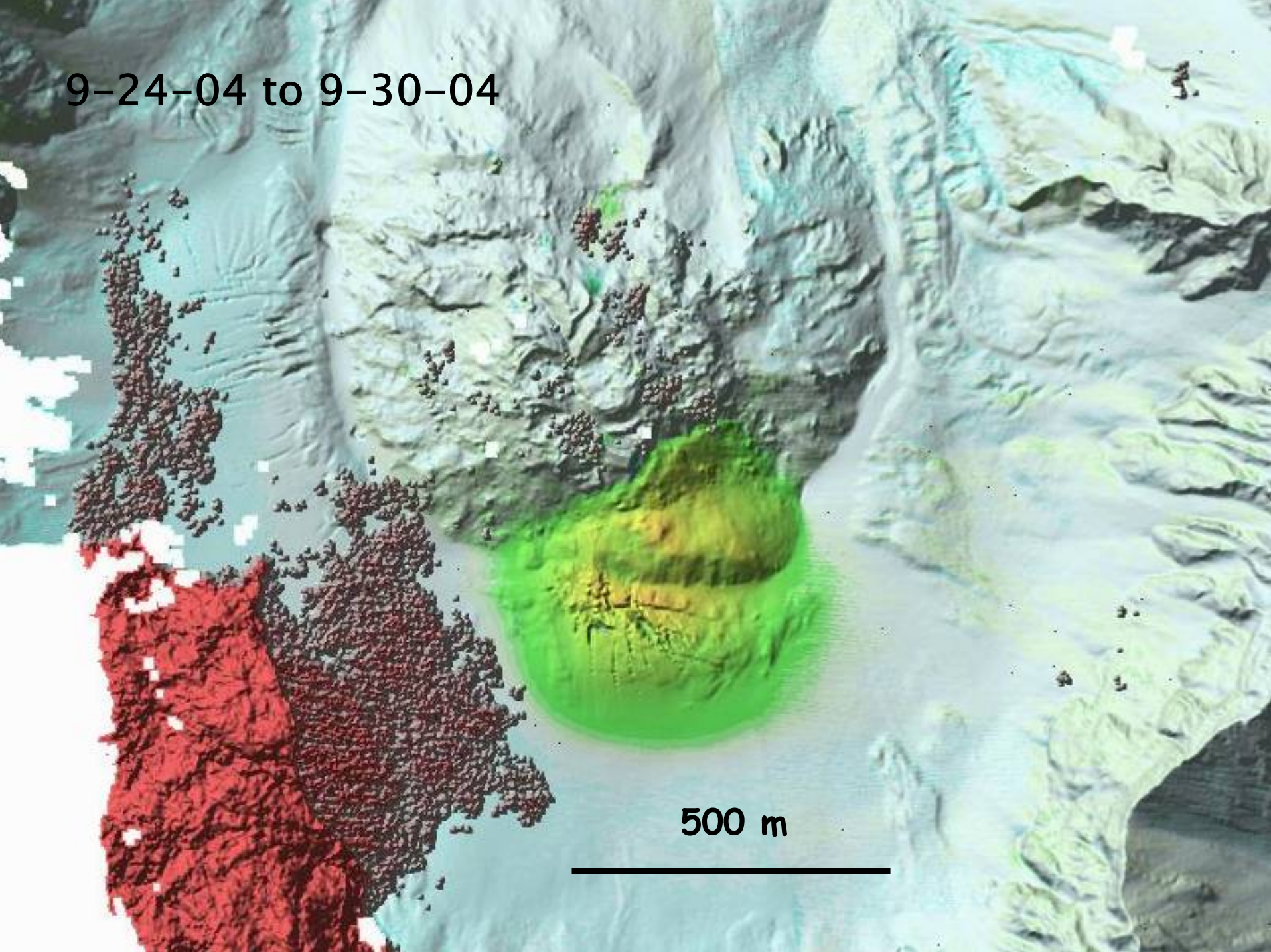

growth and advance of rock glacier
rock glaciers move
2-4 m thinning of peripheral snowfields
-30 m
-0.4 m
+20 m
+40 m
+60 m
+80 m
+100 m
collapse of NE glacier terminus
Dome growth, 5x10⁶ m³
9/26 – 10/4: 6.2 x 10⁵ m³/day
7 m³/sec
rockfall deposits
~4 m inflation of crater glacier
500 m
September, 2003
to
October 4, 2004

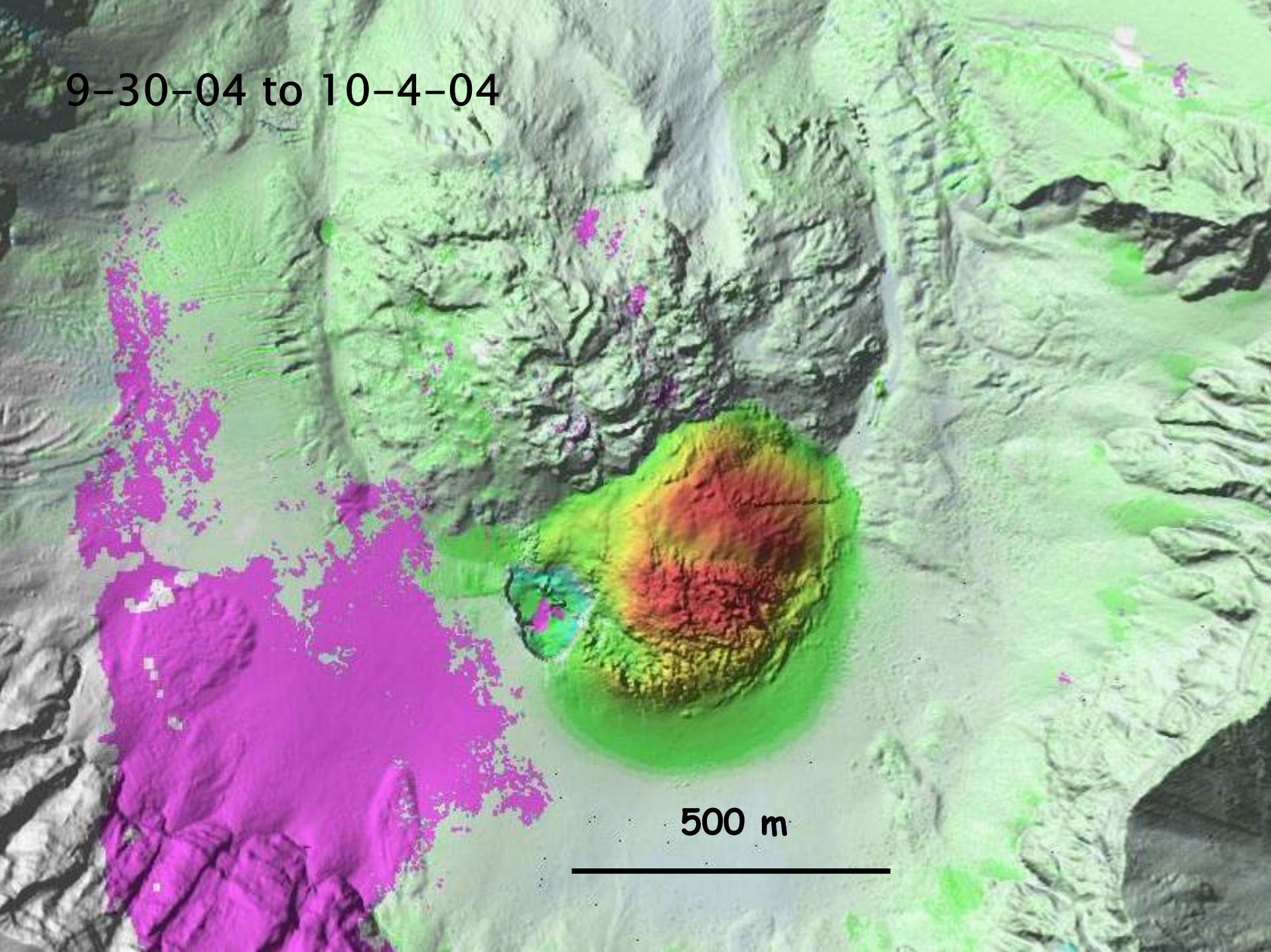
photo by Steve Malone, UW

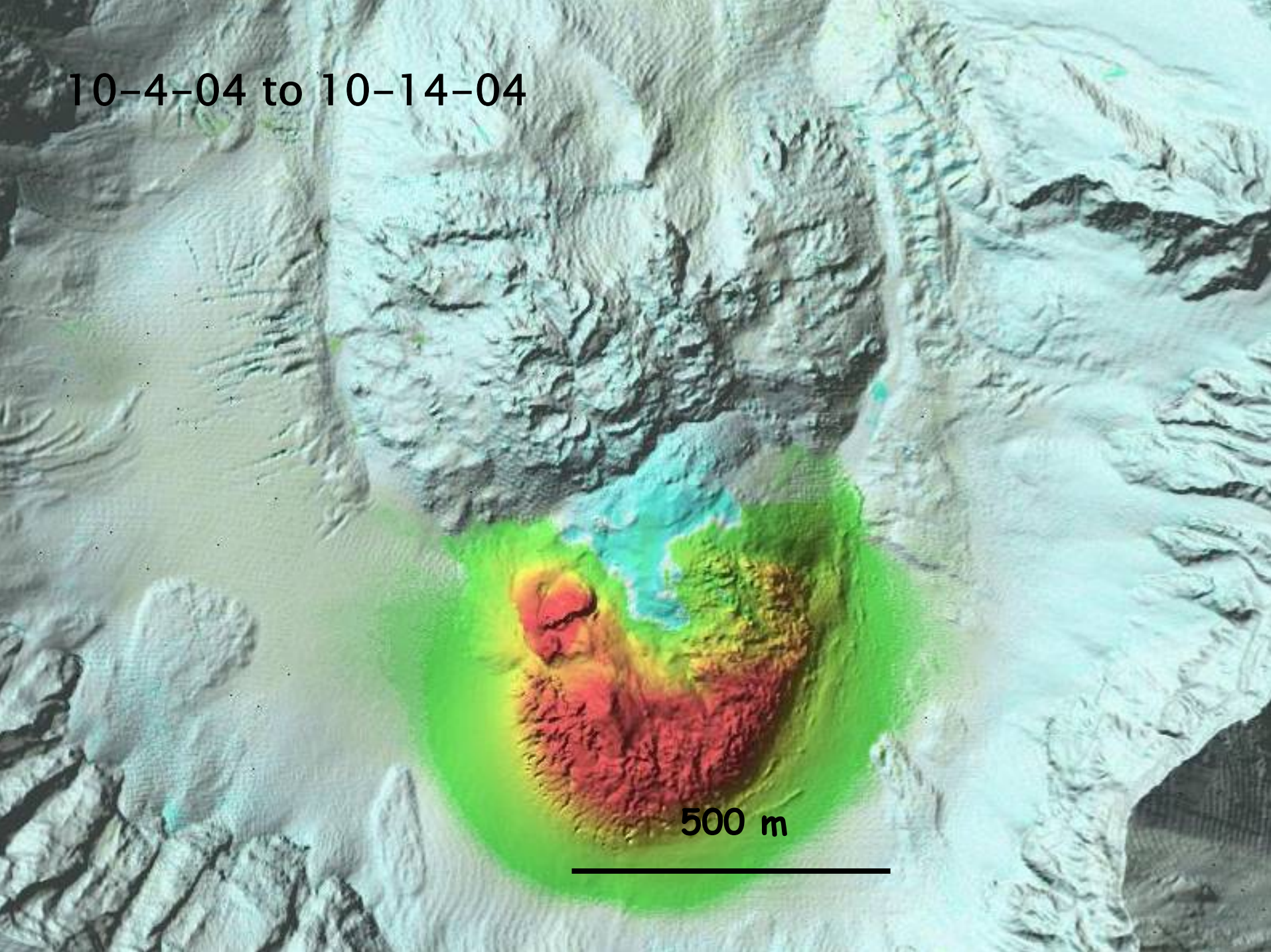


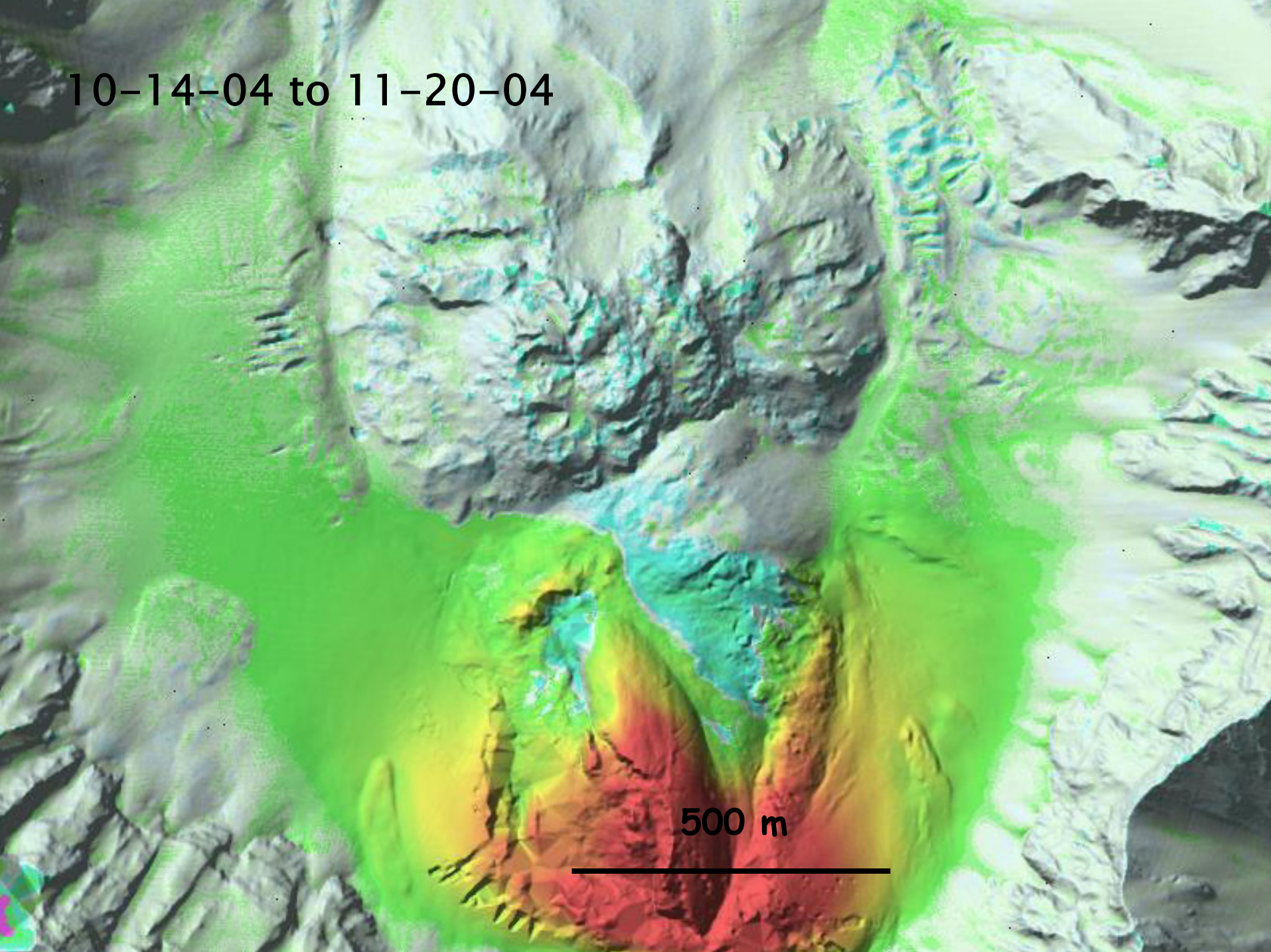
click graphic to view movie

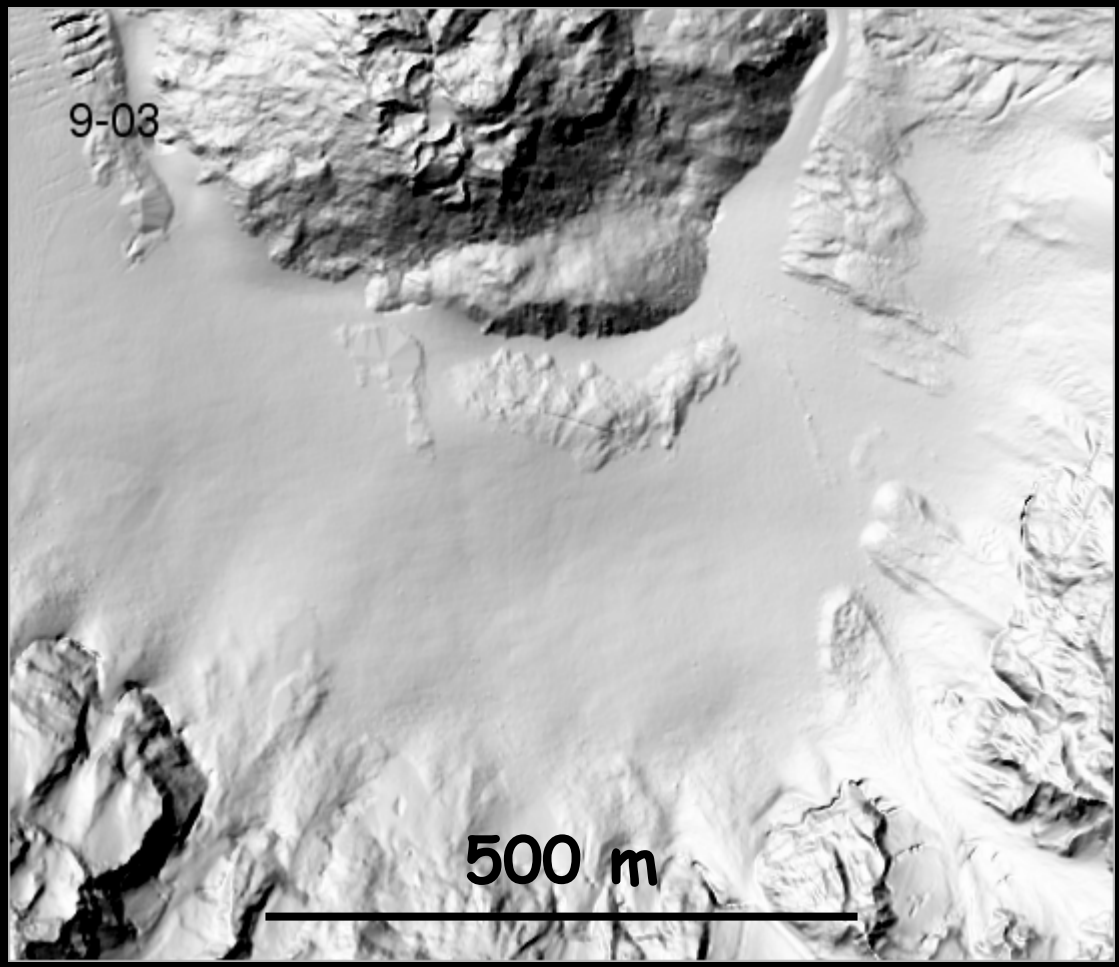

Sept 03 to 9-24-04
500 m


9-24-04 to 9-30-04
500 m

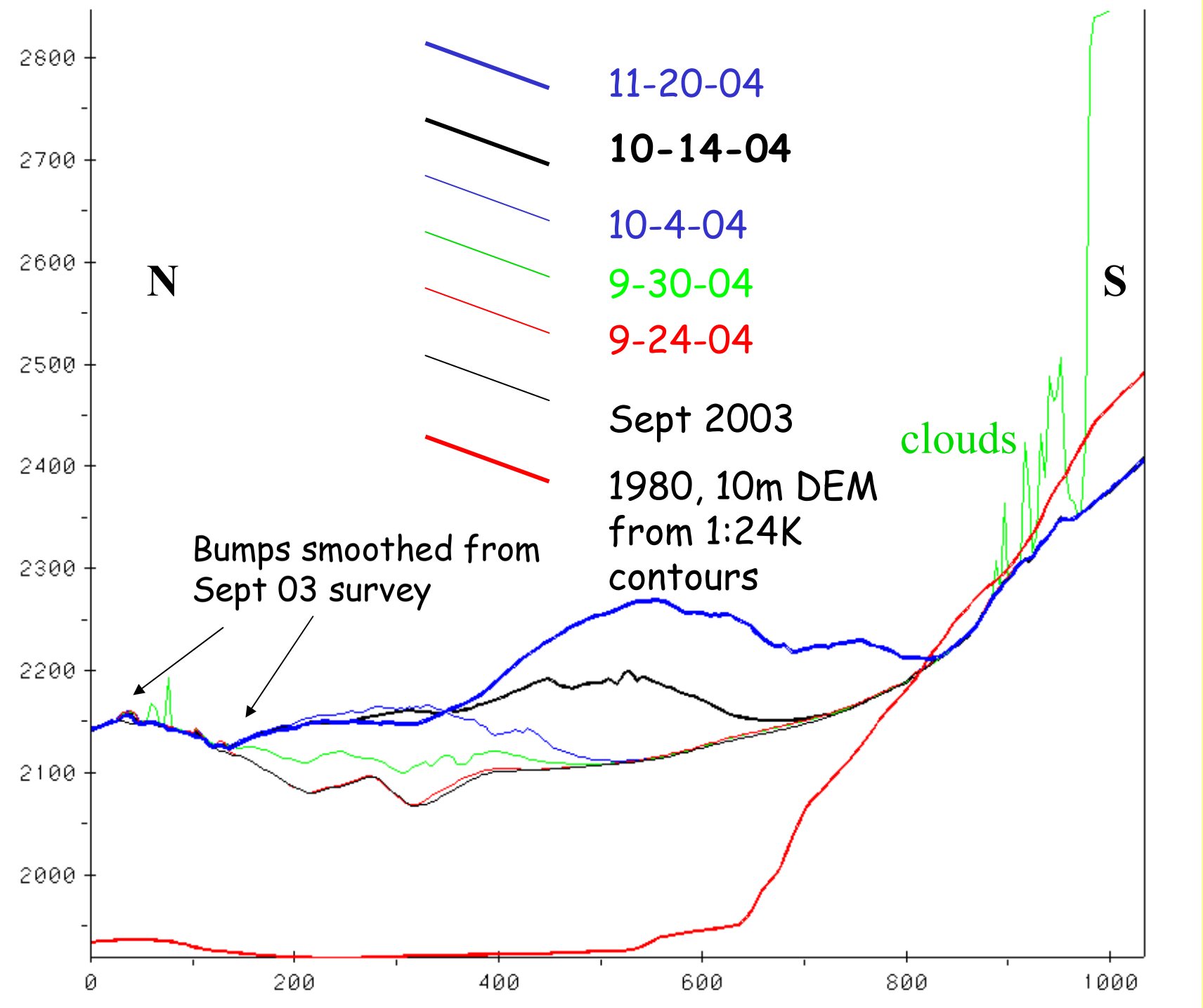

9-30-04 to 10-4-04
500 m


10-4-04 to 10-14-04
500 m

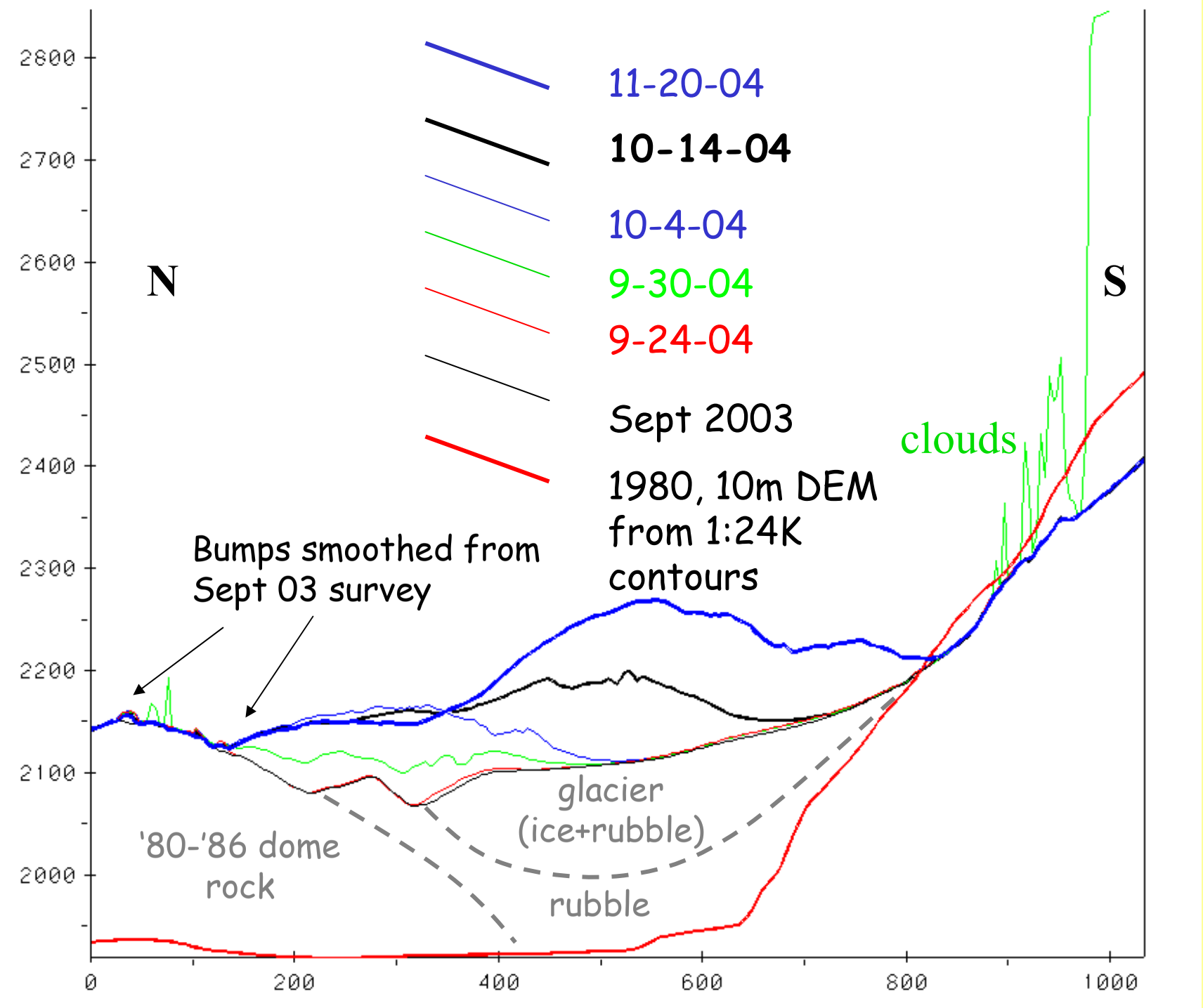

10-14-04 to 11-20-04
500 m



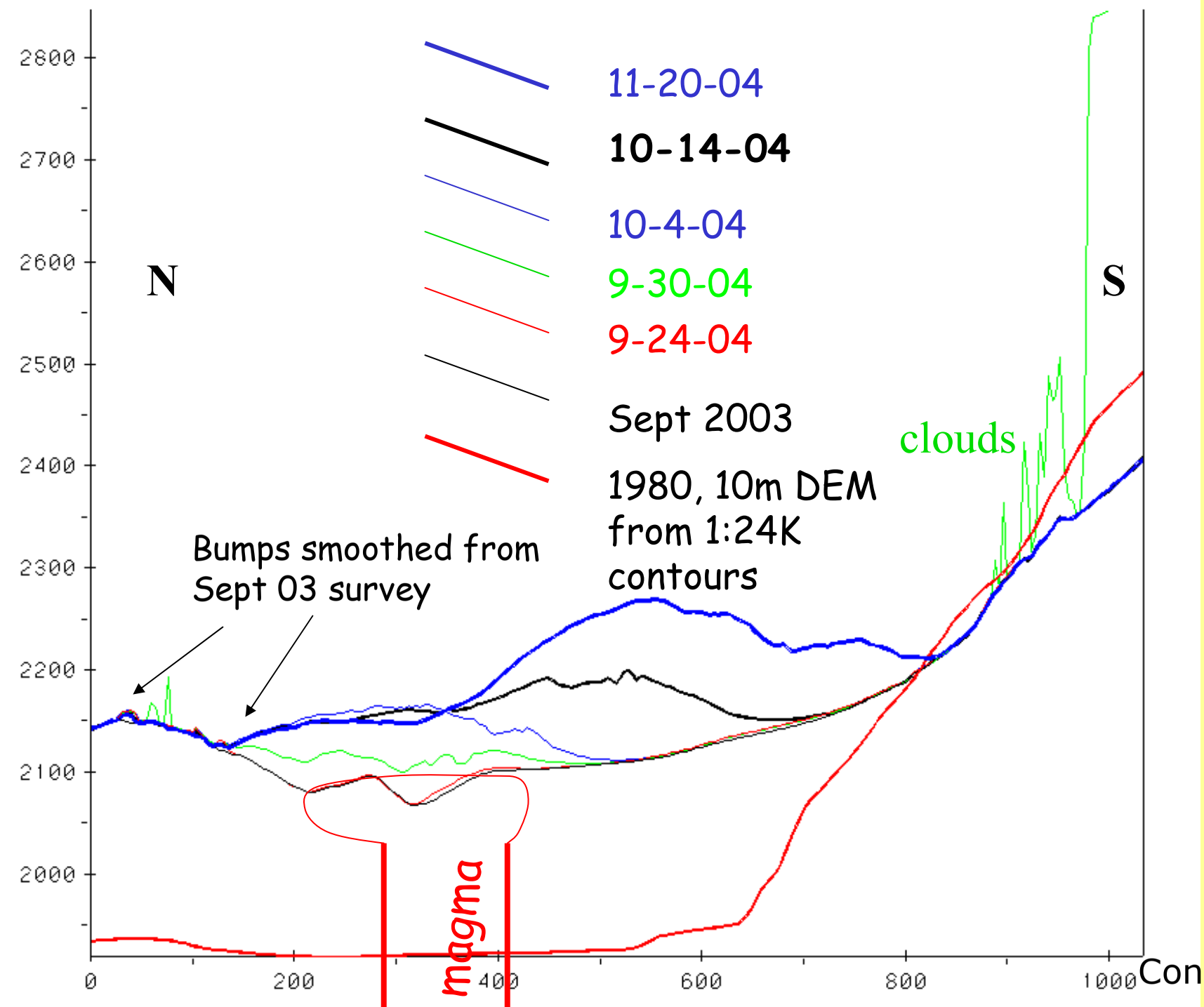
click graphic to view movie


11-20-04
10-14-04
10-4-04
9-30-04
9-24-04
Sept 2003
1980, 10m DEM from 1:24K contours
N
S
clouds
Bumps smoothed from Sept 03 survey
2800
2700
2600
2500
2400
2300
2200
2100
2000
0
200
400
600
800
1000

1x1

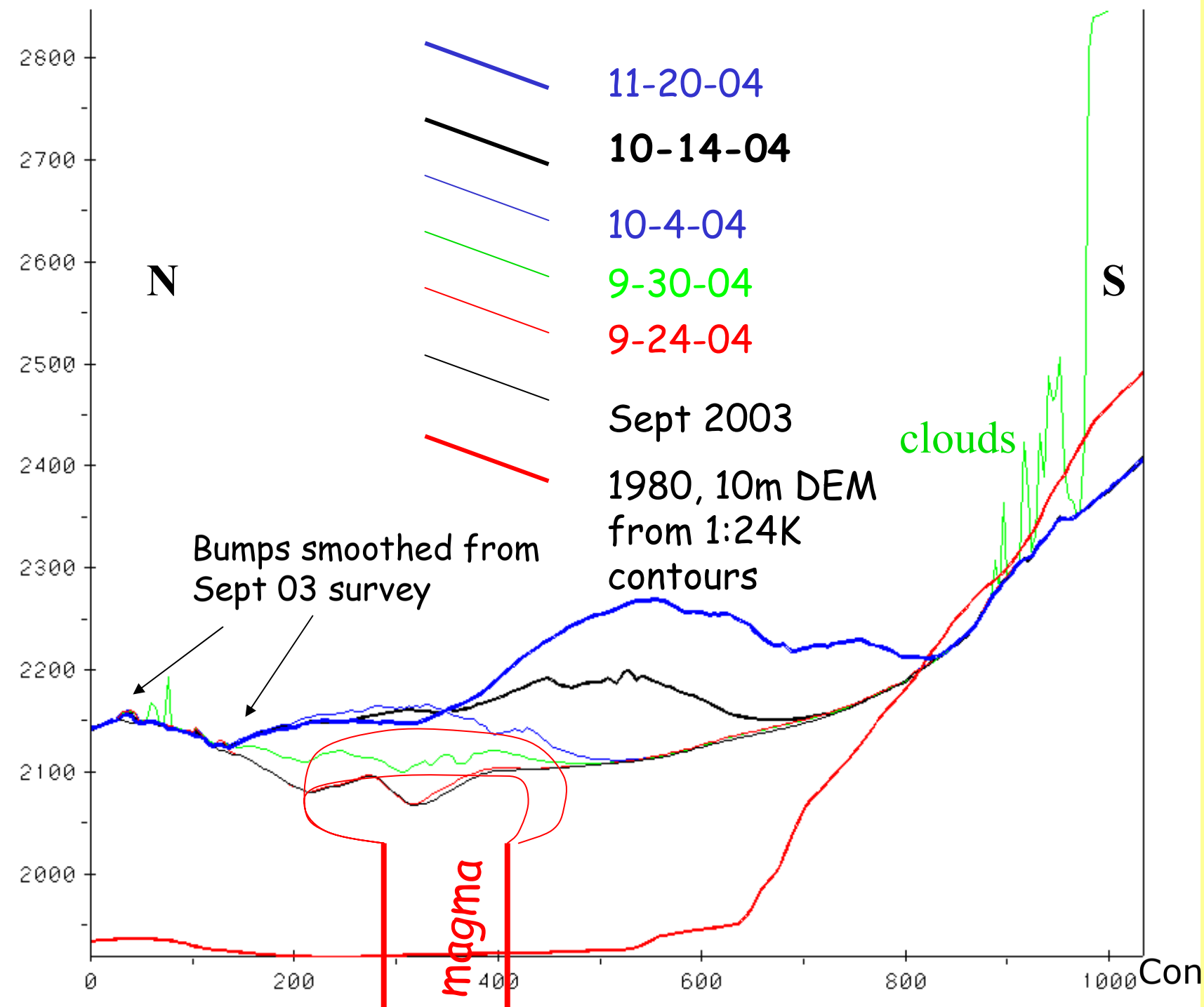

11-20-04
10-14-04
10-4-04
9-30-04
9-24-04
Sept 2003
1980, 10m DEM from 1:24K contours
N
S
clouds
Bumps smoothed from Sept 03 survey
glacier (ice+rubble)
'80-'86 dome rock
rubble
2800
2700
2600
2500
2400
2300
2200
2100
2000
0
200
400
600
800
1000

1x1



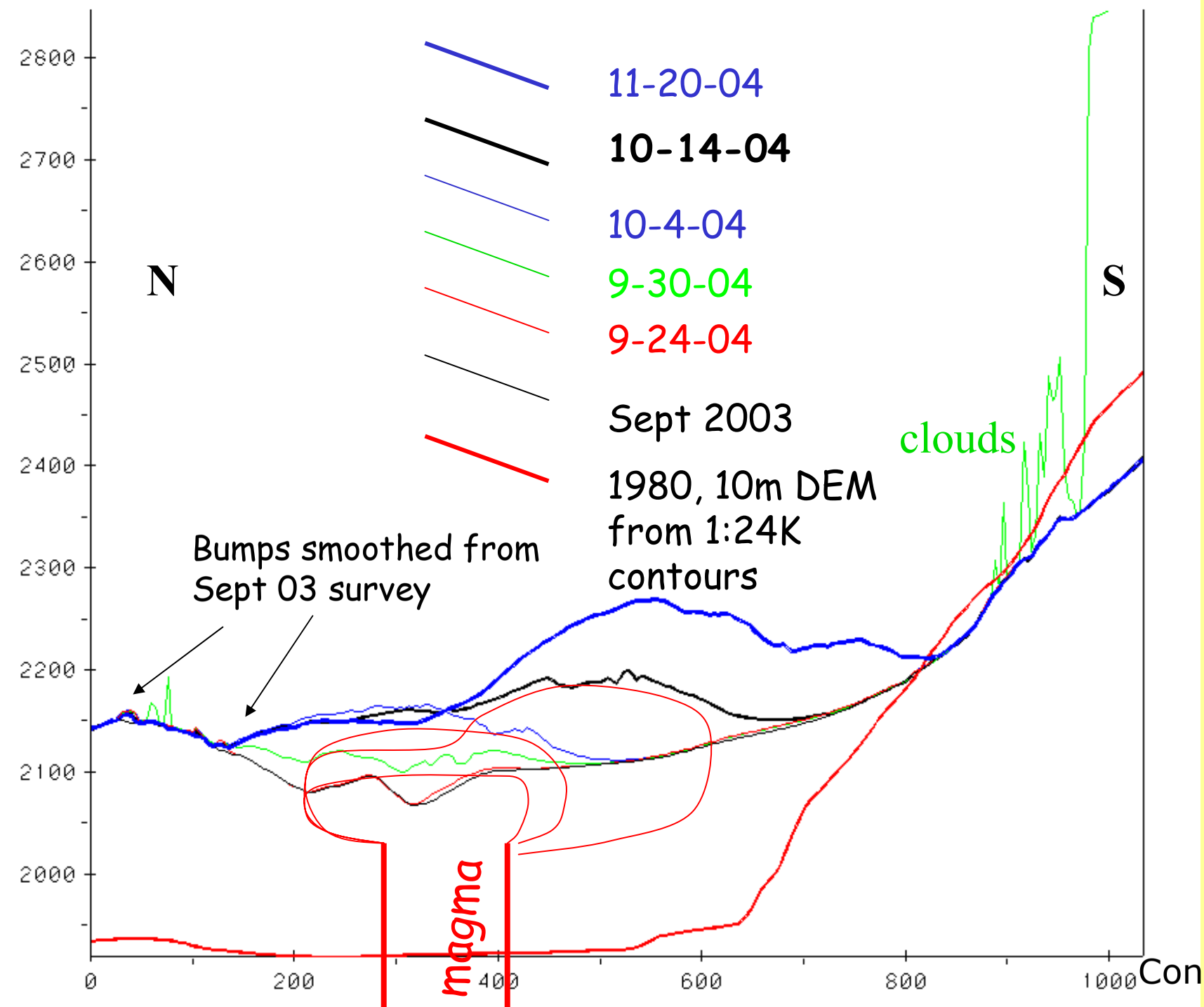
1x1

Continued



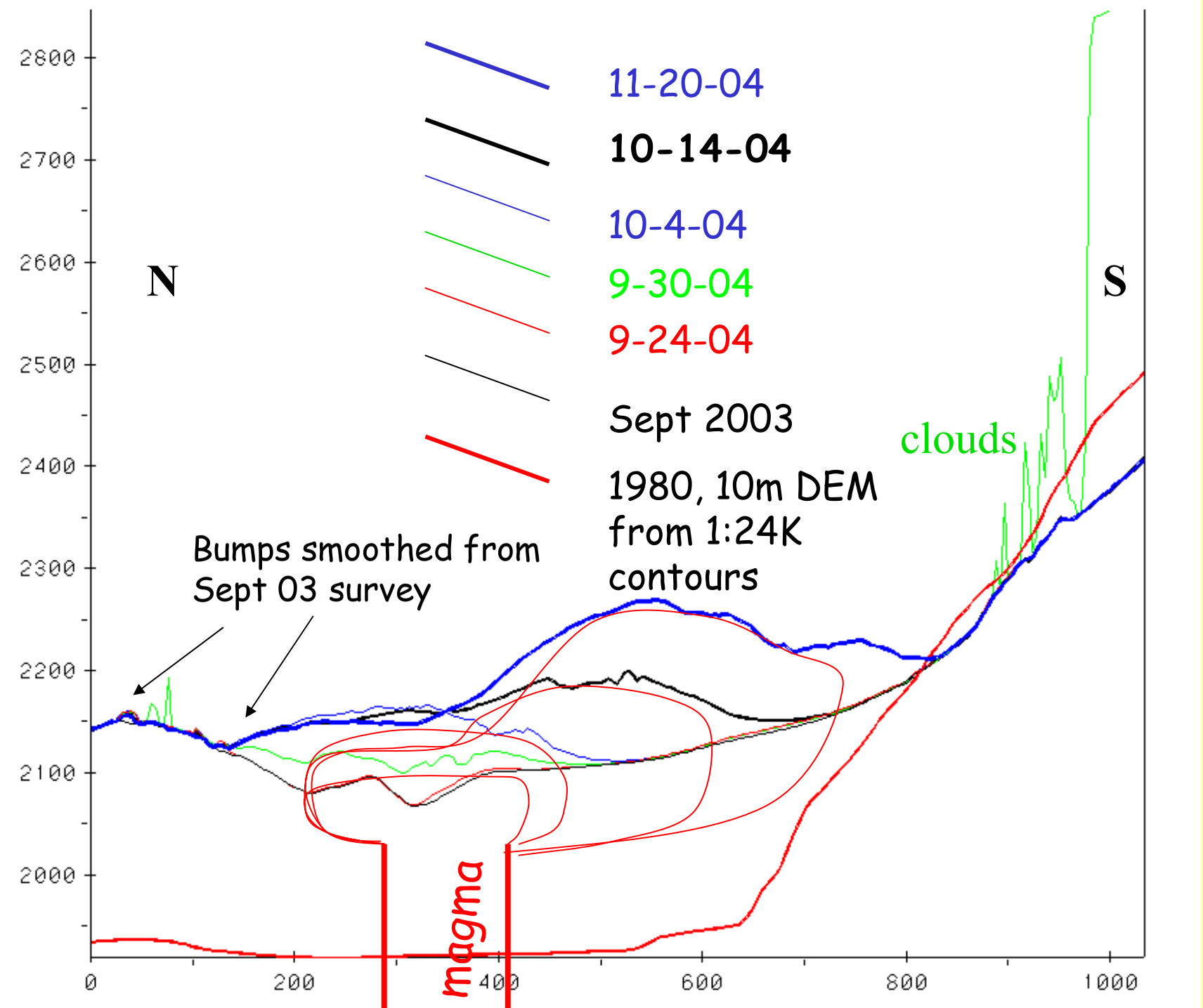
1x1

Continued



1x1

Continued


11-20-04
10-14-04
10-4-04
9-30-04
9-24-04
Sept 2003
1980, 10m DEM from 1:24K contours
N
S
clouds
Bumps smoothed from Sept 03 survey
magma
2800
2700
2600
2500
2400
2300
2200
2100
2000
0
200
400
600
800
1000

1x1

Public awareness

NASA - Laser Technology Helps Track Changes in Mount St. Helens - Mozilla Firefox
File Edit View Go Bookmarks Tools Help
http://www.nasa.gov/vision/earth/lookingatearth/mshelenslidar.html
Go
USGS Electronic Pho...
News and Opinion
CVO Menu - LIDAR
NASA - Laser Technology Helps Trac...
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
+ Text Only Site
+ Non-Flash Version
+ Contact NASA
FIND IT @ NASA :
+ GO
+ ABOUT NASA
+ NEWS & EVENTS
+ MULTIMEDIA
+ MISSIONS
+ MY NASA
+ WORK FOR NASA
+ Home
Life on Earth
+ MAIN FEATURES
+ IN EVERYDAY LIFE
- LOOKING AT EARTH
+ THE ENVIRONMENT
+ NEW TECHNOLOGIES
+ LIVING THINGS
+ IMPROVING FLIGHT
Choose another category:
+ Humans in Space
+ Exploring the Universe
FEATURE
Laser Technology Helps Track Changes in Mount St. Helens
10.25.04
U.S. Geological Survey (USGS) and NASA scientists studying Mount St. Helens are using high-tech Light Detection and Ranging (LIDAR) technology to analyze changes in the surface elevation of the crater, which began deforming in late September 2004.
Image to right: Photograph taken on October 1, 2004 of renewed volcanic activity within the crater formed by the eruption of Mount St. Helens in 1980. Recent activity, concentrated on the south side of the volcanic dome formed in the 1980s, includes uplift of a new dome from beneath the crater glacier and formation of vents by glacier melting and explosive eruptions of steam and ash. Click on image to enlarge. Credit: USGS
Vent
Glacier
New Dome
1980-86 Dome
USGS
With data derived from airborne LIDAR, scientists can accurately map, often in exquisite detail, the dimensions of the uplift and create better models to forecast volcanic hazards. LIDAR shows, in the two weeks before Oct. 4, the new uplift grew to the height of a 35-story building (110 meters or 360 feet) and the area of 29 football fields (130,000 square meters).
Rock Glaciers
Glacier Tongues
Image to left: Elevation differences in the crater were found between two airborne LIDAR surveys conducted in September 2003 and October 4, 2004. The image is a computer-generated representation of the October 4 topography. The superimposed colors
Find: lidar
Find Next
Find Previous
Highlight
Match case
Done

- Fault-scarp mapping
  - Covered by local media
  - 2003 Geol. Soci. America public lecture
- Mt St Helens work received media attention
- Invited lectures on lidar mapping
  - Regional APWA
  - NASA-AASG workshop on Remote sensing for geologic mapping

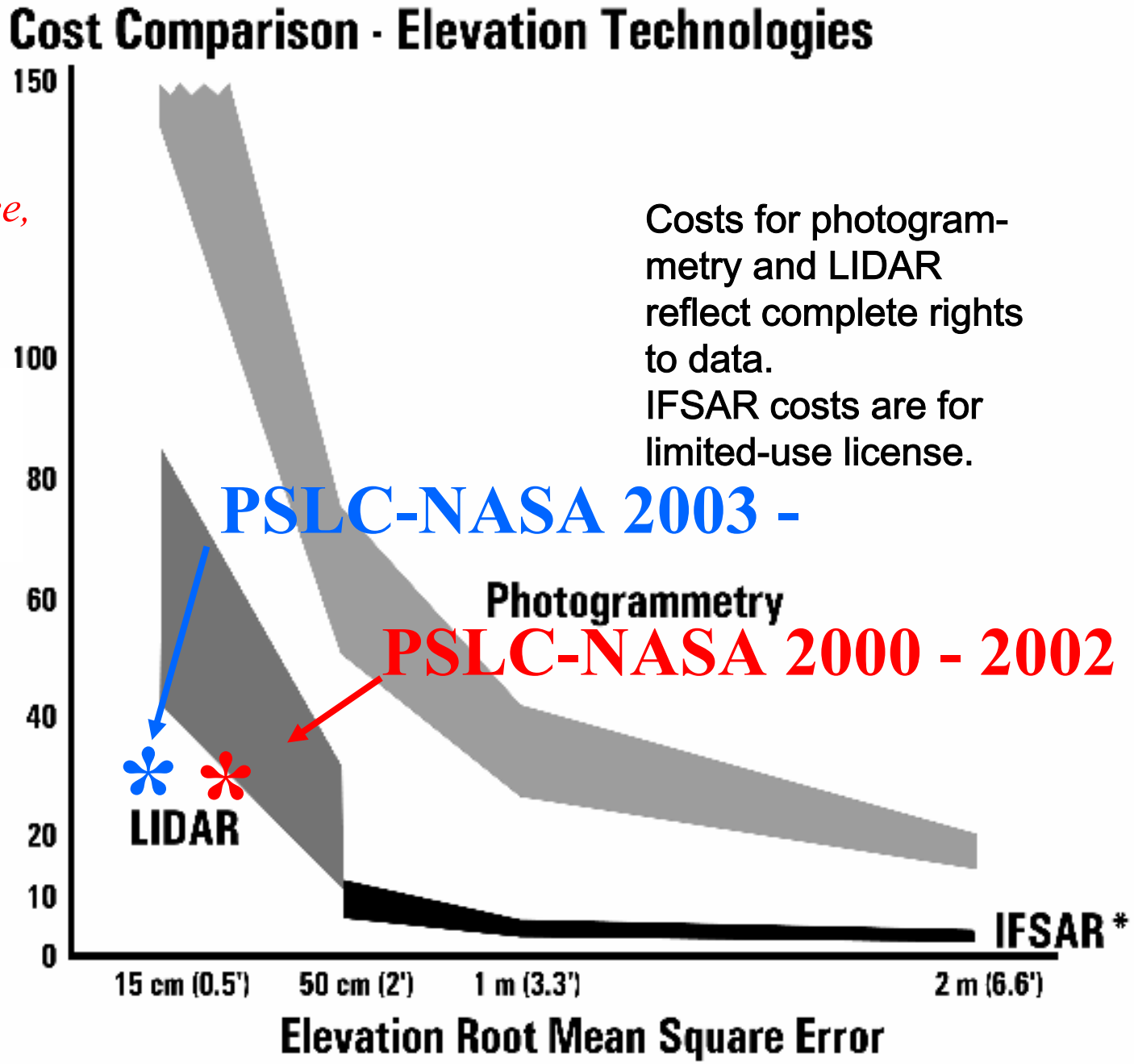
Accomplishments:

- Successfully completed planned data acquisition
  - Commercial lidar is useful in this high-relief, heavily forested terrain
- Have made significant progress on quality-assurance procedures
- Have identified fault scarps for paleoseismologists to trench
- Contributed to documentation of Fall 2004 eruption of Mount St Helens

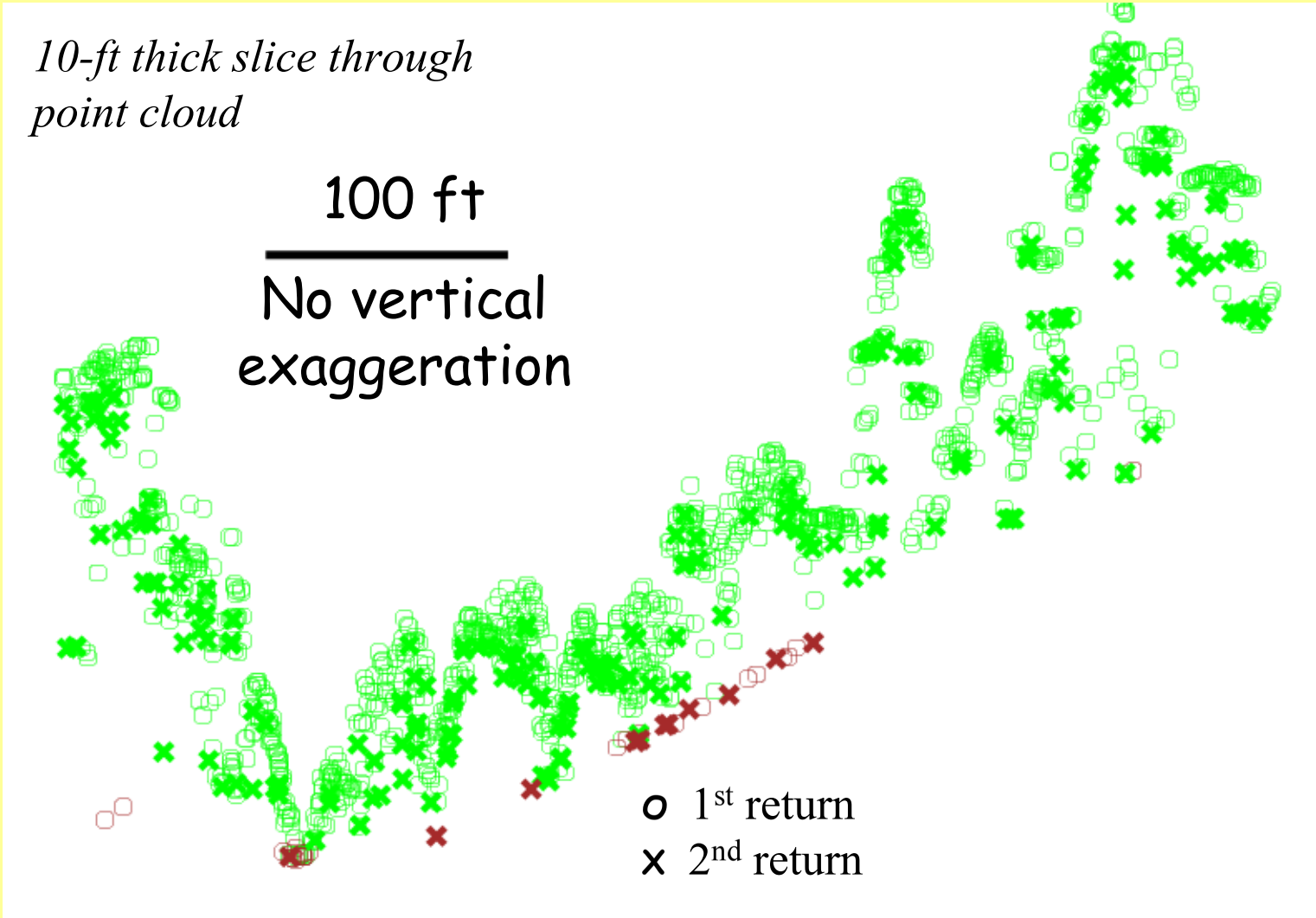
To be done:

- Assimilate remainder of late 2004 survey data
- Adapt overlap analysis to estimation of accuracy of bare-earth DEMs
- Publish our quality-assurance procedures
- Encourage forest mapping by others
- Create and publish a landslide inventory?
- **Obtain funding for further surveys**

Courtesy
Eric Constance,
USGS-NMD



To make topography, one discards most of the lidar data set



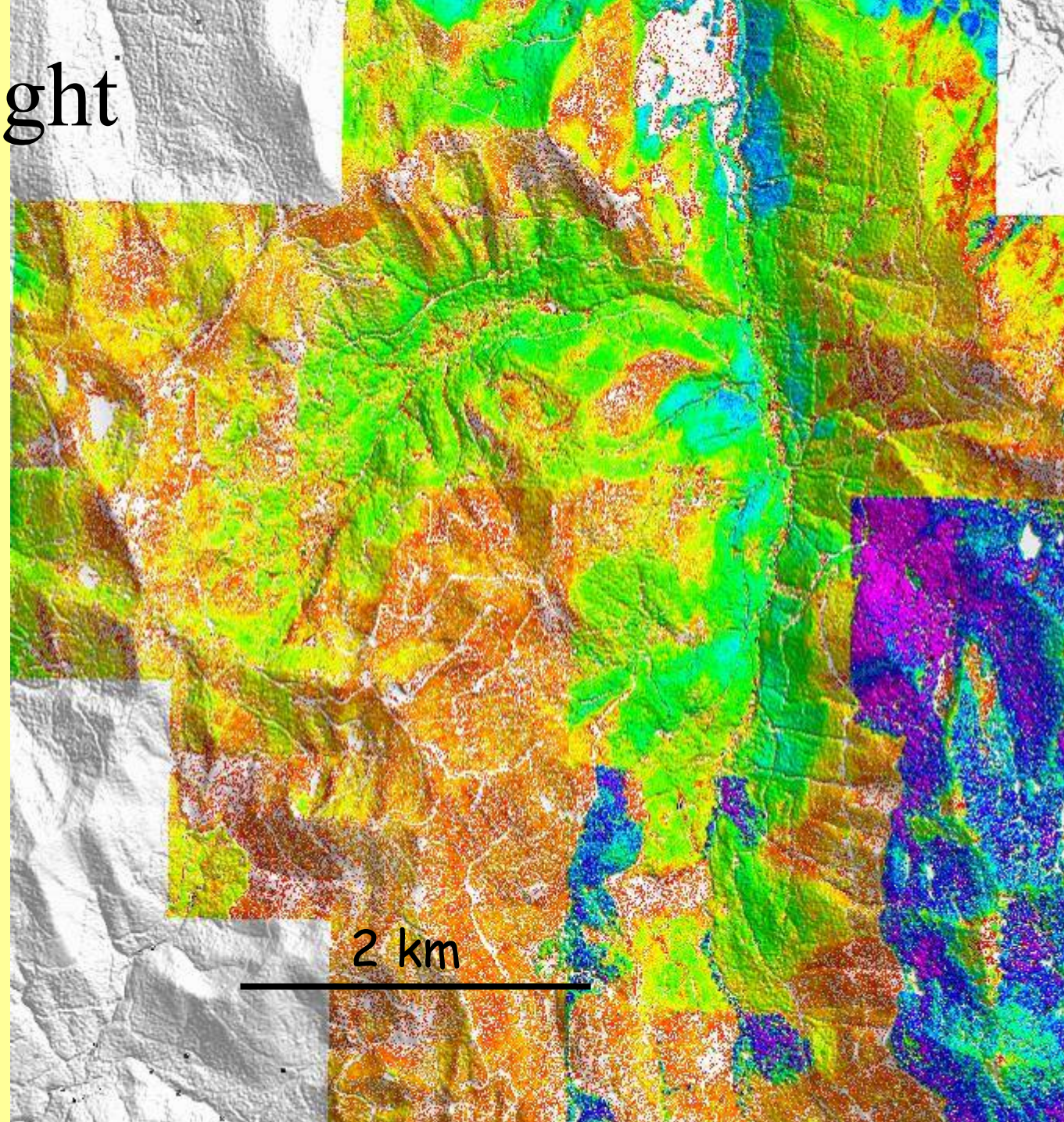
Canopy height

- 30-ft cells
- 90+ 1st returns in each cell

90th percentile height

≥150'
120'
90'
60'
30'
5'

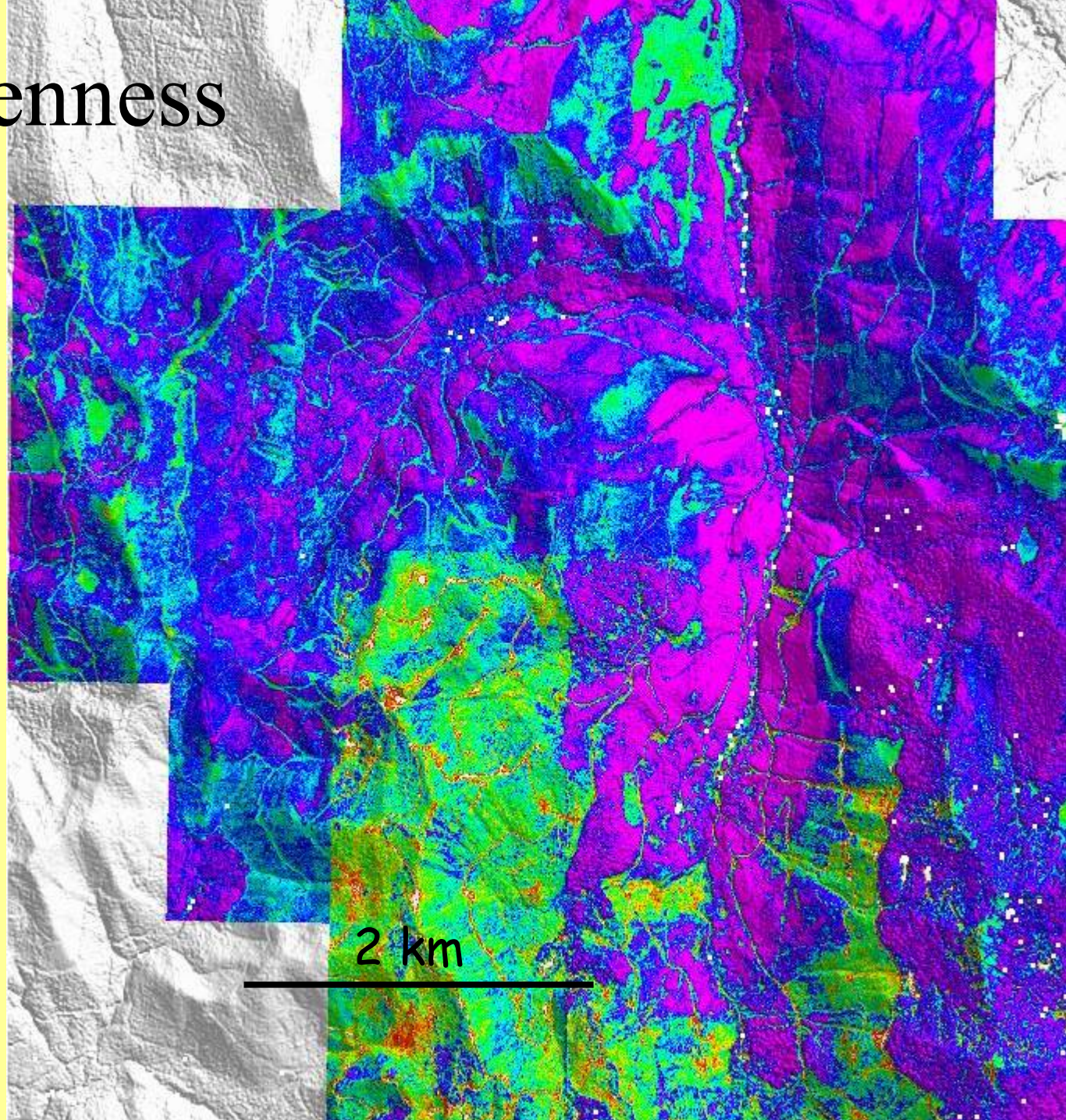
canopy calculations are fully automated



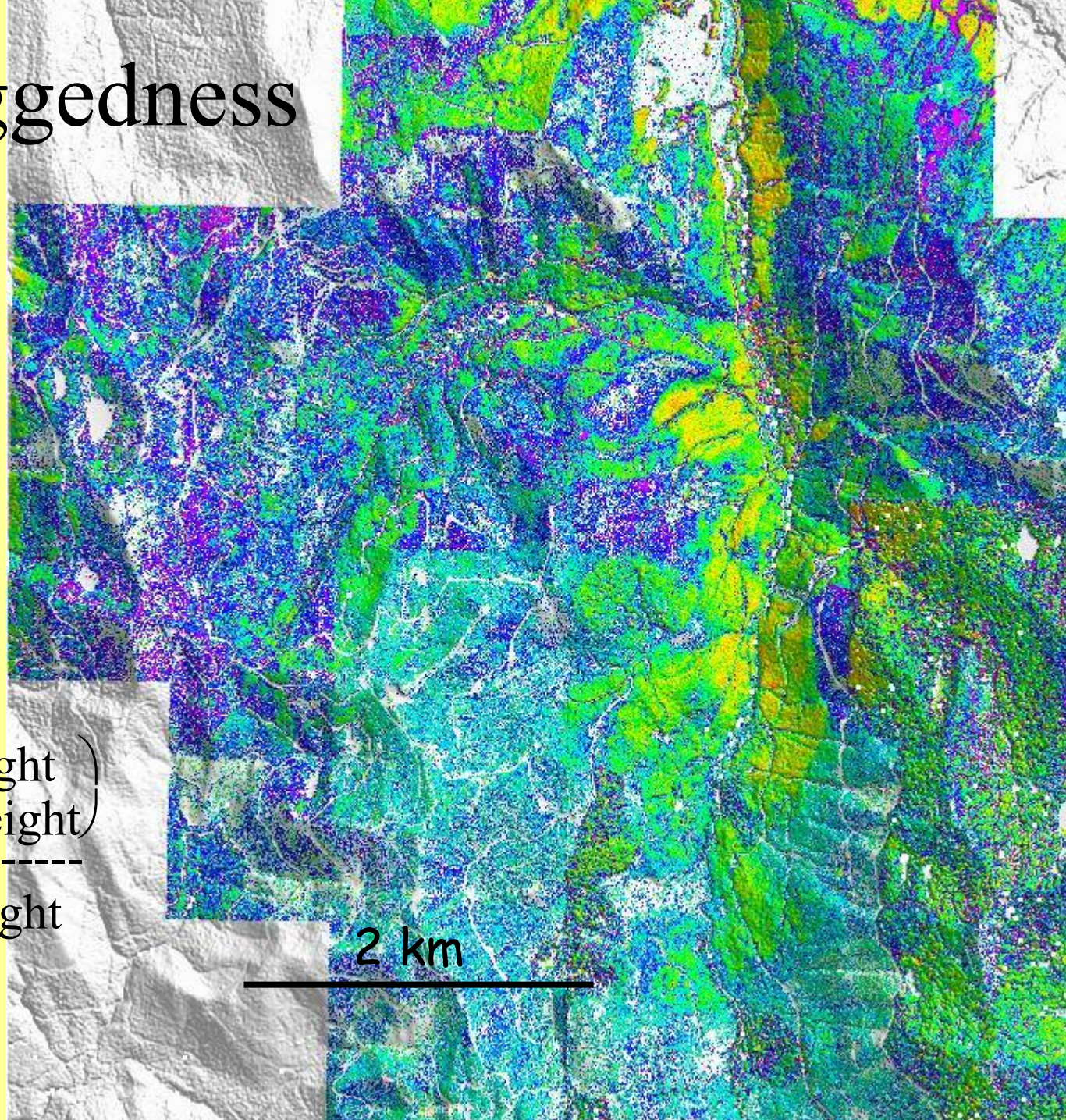
Canopy openness

fraction 1st returns on ground

0%
20%
40%
60%
80%
97%



Canopy raggedness



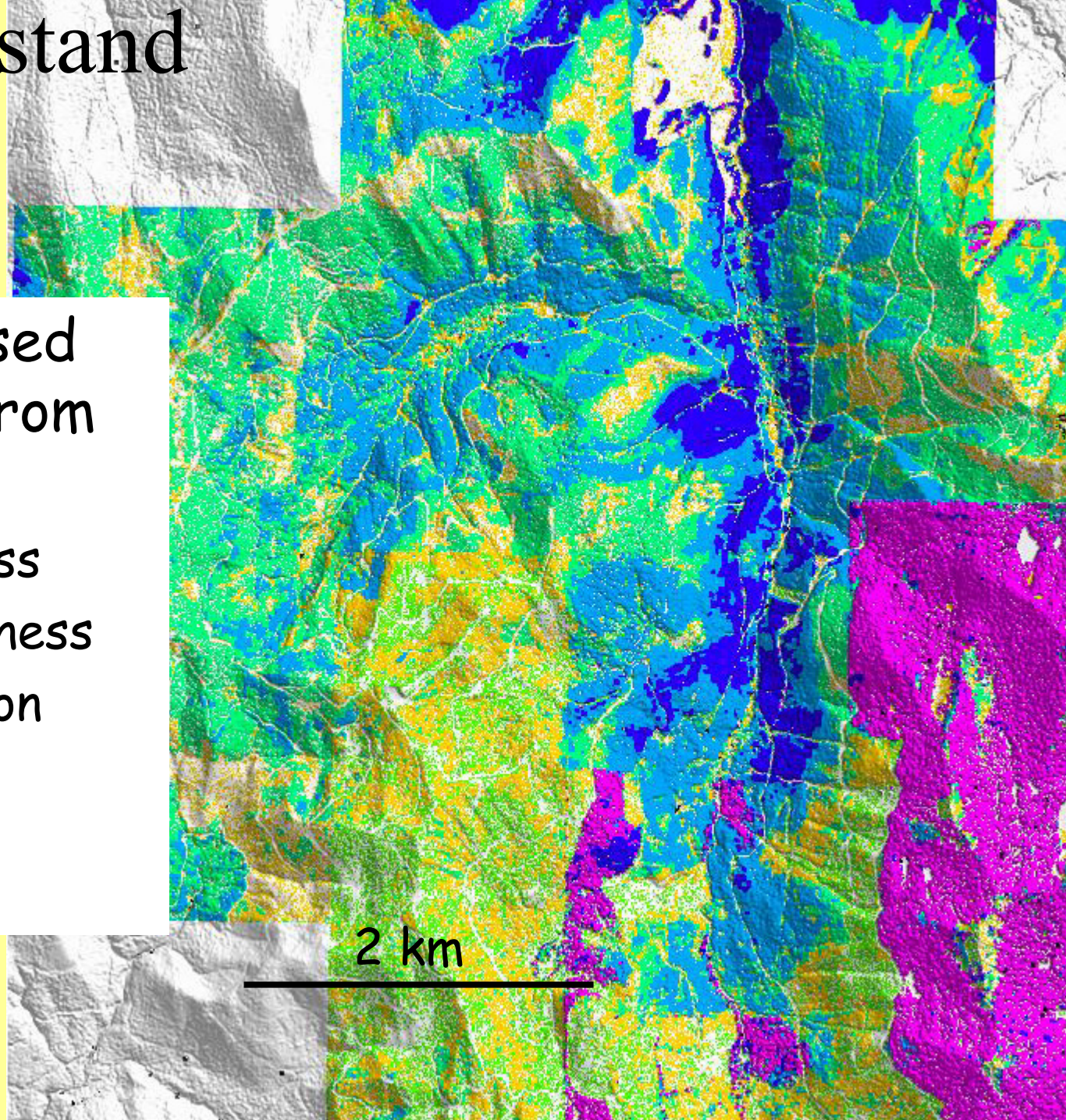
$$\frac{\left(75^{th}\text{ percentile height} - 25^{th}\text{ percentile height}\right)}{90^{th}\text{ percentile height}}$$

Automatic stand mapping

An unsupervised classification from

- canopy height
- canopy openness
- canopy raggedness
- ground elevation

Despeckled



Automatic stand mapping

- Predicting sources of large woody debris in streams
- Modeling stream temperatures
- Mapping fire hazards
- …

Map forest characteristics instead of sampling them

Better answers to questions about continuity in forest landscapes